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A DESIGN PROCESS USING TOPOLOGY OPTIMIZATION APPLIED TO FLAT PRESSURIZED STIFFENED PANELS

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Ce mémoire intitulé:

A DESIGN PROCESS USING TOPOLOGY OPTIMIZATION APPLIED TO FLAT PRESSURIZED STIFFENED PANELS

présenté par : DUGRÉ Alexis

en vue de l'obtention du diplôme de : Maîtrise ès sciences appliquées

a été dûment accepté par le jury d'examen constitué de :

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DÉDICACE

À mes parents, mon frère, mes amis et Stéphanie

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RÉSUMÉ

La conception de structures légères et efficaces est essentielle dans l'industrie aérospatiale pour atteindre les performances voulues. Le processus de conception classique consiste à générer un premier concept basé sur l'expérience et la connaissance et à l'améliorer par la suite au cours de plusieurs itérations. L'émergence de l'optimisation topologique change ce processus puisque cette méthode peut montrer la distribution optimale de la matière afin de générer un concept initial amélioré. Ceci peut réduire le temps du cycle de conception et améliorer la performance finale.

L'optimisation topologique pour la conception de structures aéronautiques a été appliquée dans des études de cas industrielles fructueuses. Cela encourage l'exploration de cette technologie chez Bombardier Aéronautique afin d'évaluer ses bénéfices potentiels et de définir les meilleures pratiques. L'objectif de ce projet est d'explorer l'application de l'optimisation topologique pour la conception d'une cloison de pressurisation arrière d'avion et de développer un nouveau processus de conception basé sur les connaissances acquises.

Une revue de littérature est d'abord conduite afin de se familiariser avec le sujet et les travaux existants. Cette revue met l'emphase sur la technique d'optimisation topologique (**S**olid **I**sotropic **M**aterial with **P**enalization (SIMP)) et le processus de conception l'utilisant. Cette méthode est sélectionnée car elle est utilisée couramment et elle est implémentée dans des logiciels commerciaux disponibles. Dans cette étude, l'optimisation topologique est utilisée pour déterminer le raidissement optimal pour supporter la peau pressurisée de la cloison plane. Cependant, aucune application industrielle du processus pour la conception de structures pressurisée n'existe à notre connaissance. Aussi, la recherche sur le raidissement optimal de plaque par optimisation topologique est limitée puisque des contraintes typiques de conception comme la contrainte du matériau et le déplacement ne sont pas considérées. De plus, les résultats sont comparés à une plaque d'épaisseur uniforme ce qui n'est pas représentatif d'un concept de panneau raidi classique. Afin de parer à ce manque de connaissances et d'explorer l'application de l'optimisation topologique pour le raidissement de panneaux pressurisé, l'étude de cas de la

cloison d'avion arrière est simplifiée à une plaque rectangulaire sous pression. L'optimisation topologique est utilisée pour déterminer le raidissement optimal et les résultats sont comparés avec un concept typique. L'expérience et les connaissances acquises durant cette étude simplifiée sont ensuite utilisées pour développer le nouveau processus de conception basé sur les principes de la conception axiomatique. La conception axiomatique est une méthode de conception mettant l'emphase sur la fonctionnalité permettant d'encadrer la conception d'un produit. Cette dernière est utilisée pour supporter le processus de conception par optimisation topologique et surmonter les problèmes identifiés.

Les résultats du travail peuvent être divisés en deux aspects.

Premièrement, l'étude de la plaque rectangulaire met en évidence plusieurs défis associés à la conception de panneaux raidis sous pression par optimisation topologique. La génération de raidissement n'est pas directe puisque le résultat n'est pas unique. La méthode SIMP converge vers des optimums locaux et les concepts obtenus sont sensibles à la mise en place de l'optimisation et aux conditions frontières. Aussi, l'effet de membrane non linéaire associé aux plaques sous pression ne peut pas être capturé par l'analyse linéaire par éléments finis utilisée par le solveur ce qui peut affecter la validité du raidissement suggéré. De plus, l'interprétation du raidissement est difficile puisque les raidisseurs modélisés par l'espace de conception peuvent être soumis à un chargement complexe. La combinaison de chargement en torsion et en flexion rend l'utilisation efficace d'une section de poutre compliquée. Finalement, une estimation de la performance du concept d'optimisation topologique a montré que la masse n'était pas réduite significativement par rapport à un concept typique et intuitif. L'étude démontre qu'il est important d'explorer l'espace de conception avec plusieurs optimisations topologiques de façon à obtenir une compréhension globale de la fonctionnalité des caractéristiques observées avant d'interpréter un concept.

Deuxièmement, le nouveau processus de conception combinant la conception axiomatique et l'optimisation topologique s'est avéré une approche innovante et efficace pour la génération de concepts. Dans ce processus, l'optimisation topologique est seulement utilisée comme un outil encadré par la conception axiomatique. Elle permet d'explorer l'espace de conception et d'obtenir de l'information concernant la distribution optimale de la matière. Cette information aide à définir les requis fonctionnels (FRs - « Functional Requirements ») de la structure. Cette étape d'interprétation fonctionnelle force le concepteur à comprendre l'origine des caractéristiques observées ce qui permet d'éviter une interprétation directe du résultat de l'optimisation topologique. L'interprétation physique peut ensuite être effectuée en sélectionnant des paramètres de conception (DPs - « Design Parameters ») qui remplissent les FRs définis précédemment. Le respect des deux axiomes (indépendance des fonctions et minimisation de l'information) évite aussi les couplages dans le concept interprété et maximise ses chances de succès. Finalement, la conception axiomatique assure que des contraintes comme la fabrication et le coût soient considérées dans l'interprétation. Le processus est appliqué avec succès à la conception de la cloison de pressurisation arrière d'un avion.

Cette recherche contribue au domaine de la conception par optimisation topologique, car elle présente une des première applications complète (du concept jusqu'au dimensionnement) connue de cette technique pour la conception d'un panneau raidi pressurisé. La connaissance acquise est partagée avec la communauté scientifique par l'entremise d'un article de journal soumis à la revue *Structural and Multidisciplinary Optimization*. Cette recherche présente aussi un nouveau processus de conception définissant les bases d'une méthode systématique et innovante pour générer des concepts de structures. Il s'agit de la première combinaison connue de la conception axiomatique et de l'optimisation topologique étant toutes deux une approche de conception puissante. Le processus peut être utilisé pour n'importe quel composant structurel et il a donc un grand potentiel d'application. Toutefois, ce dernier n'a pas pu être testé sur un grand nombre de cas ce qui est nécessaire pour atteindre la maturité.

ABSTRACT

The design of light and efficient structures is essential in aerospace industry to meet performance targets. The typical design process consists of generating a first design based on experience and knowledge and improving it during several iterations. The emergence of topology optimization changes this process since this technology can show optimal material placement in order to generate an improved initial concept. This can reduce design cycle time and improve the final performance.

Topology optimization for the design of aircraft structures has been applied in successful industrial case studies. This encourages the exploration of this technology within Bombardier Aerospace in order to evaluate its potential benefit and define best practices. The objectives of the project are to explore the application of topology optimization for the design of an aircraft's rear pressure bulkhead and to develop a design process based on the acquired knowledge.

A literature review was first conducted in order to improve the knowledge on topology optimization. The review focussed on the topology optimization technique (**S**olid **I**sotropic **M**aterial with **P**enalization (SIMP)) and the design process using it. This method is selected because it is commonly used and it is implemented in available commercial softwares. In this study, topology optimization is used to determine the optimal stiffener layout to support the pressurized skin of the flat bulkhead. However, no industrial application of the process for the design of pressurized structures exists to our knowledge. Also, the research on optimal plate stiffening using topology optimization is limited as it does not consider typical design constraints such as stress and displacement. Moreover, the results are compared to a uniform thickness plate which is not representative of a typical stiffened panel design. In order to fill this knowledge gap and explore the application of the topology optimization for pressurized plate stiffening, the bulkhead design case is simplified as a flat rectangular pressurized plate. Topology optimization is used to determine an optimal stiffener layout and results are compared with a typical design. The experience and knowledge acquired with this simplified study is then used to develop the new design process based on axiomatic design principles. Axiomatic design is a design

methodology focussing on functionality that supports product design. It is used to support topology optimization design process and overcome the identified challenges.

The results of this work can be divided into two aspects: First, the study of the rectangular plate highlights several challenges associated to the design of stiffened pressurized panels using topology optimization. The generation of a layout is not straightforward since the result is not unique. The SIMP method converges to local optimums and the resulting layouts are sensitive to optimization set-up and boundary conditions. Also, the non-linear membrane effect associated to pressurized plate cannot be captured by the linear finite element analysis used by the solver which can affect the validity of the layouts suggested. Moreover, the interpretation of the layouts is also challenging since the stiffeners modelled by the design space may sustain complex loading. The combination of torsion and bending load makes the use of efficient cross-section difficult. Finally, a performance estimation of the topology design showed that no significant weight savings are achieved compared to a typical and intuitive design. The study demonstrates that it is important to explore the design space with several topology optimizations in order to get a global understanding of the functionality of the features observed before interpreting a concept.

Second, the new design process combining axiomatic design and topology optimization proved to be an innovative and efficient approach for the generation of design concepts. In this process, topology optimization is only used as a tool in the axiomatic design framework. It allows exploring the design space and obtaining information concerning optimal material placement. This information helps defining the functional requirements (FRs) of the structure. This functional interpretation step forces the designer to understand the origin of the feature observed and avoids a direct interpretation of the topology result. The physical interpretation can then be performed by selecting design parameters (DPs) that fulfill the FRs previously defined. The respect of the two axioms (independence and information) also avoids coupling in the concept and maximize its chances of success. Finally, axiomatic design ensures that constraints such as manufacturability and cost are considered during the interpretation. The process is successfully applied for the design of a rear aircraft pressure bulkhead.

This research contributes to the topology optimization design domain as it presents one of the first complete application (from concept to sizing) known of this technique for the design of stiffened pressurized plates. The acquired knowledge is shared to the scientific community by a paper submitted to the *Structural and Multidisciplinary Optimization* journal. This research also presents a new design process that sets the basis of a systematic and innovative methodology to generate structural design concepts. It is an original combination of axiomatic design and topology optimization which are two powerful design approaches. The process can be used for any structural component and therefore have great potential applications. However, it has not been tested on a large number of cases which is necessary to reach maturity.

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LIST OF ABBREVIATIONS

A	Section Area
CN	Customer Need
CON	Constraint
δ	delta: Displacement
DP	Design Parameter
E	Young Modulus
FR	Functional Requirement
G	Shear Modulus
I	Second Moment of Inertia
J	Torsional constant
L	Length measure
MAXDIM	Maximum member size control
MINDIM	Minimum member size control
ρ	rho: Element density design variable
p	Penalization power of SIMP material interpolation scheme
P	Pressure
$\mathbf{K}$	Element stiffness matrix
$\bar{\mathbf{K}}$	Adjusted Element stiffness matrix of SIMP material interpolation scheme
PV	Process Variable
σ	sigma: Stress
SIMP	Solid Isotropic Material with Penalization
VF	Volume fraction
ν	nu: Poisson coefficient

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INTRODUCTION

The reduction of design cycle time and the improvement of the performance are critical aspects of any structural design in the aerospace industry. The typical design process starts by creating a first concept based on the experience and the knowledge of the designer. The design then goes through several iterations of validation and optimisation in order to reach performance targets while meeting structural requirements and constraints. This approach is rather long and the results obtained are not necessarily optimal because of the empirical nature of the initial design.

The arrival of topology optimization in industry changes this design process. This approach is used to visualize optimal material placement in a design space for given loads and boundary conditions. The first design concept is therefore based on the result of an optimization which can reduce design cycle time and help acquire the desired performance. Several successful industrial applications encouraged the exploration of this approach for the design of a primary structural component at Bombardier Aerospace. The objective of this project is to investigate the opportunity to apply topology optimization for the design of a rear aircraft pressure bulkhead as well as to define a new design process with the acquired knowledge.

Several challenges associated to the application of topology optimization for the design of pressurized plates are identified and presented in a submitted journal paper. A new design process combining axiomatic design and topology optimization is then developed to overcome the difficulties associated to the generation and the interpretation of design concepts using topology optimization.

Chapter one presents a literature review and the background of the topology optimization design process. Two successful industrial case studies are summarized. It also explains the theory behind the most usual implementations of topology optimization (density method). The aircraft pressure bulkhead is also introduced and its similarity with the design of a flat pressurized stiffened plate is discussed. A critical review of optimal plate stiffening using topology optimization is finally conducted. The findings of the review are then synthetized and two research questions are posed.

Chapter two integrates a submitted journal paper that discusses the challenges associated to the use of topology optimization for the stiffening of flat pressurized plate. It presents a simplified design case inspired from the bulkhead that allows isolating the effect of the pressure load case that is specific to the problem. It compares the performance of a topology design with an intuitive and typical design. The knowledge gathered for this specific case highlights the difficulties arising when using the topology design approach which helps defining a new design process.

Chapter three presents the new design process where topology optimization is used as an exploration tool within the axiomatic design framework. This combination of conceptual design approaches is an innovative proposal that allows overcoming several of the identified challenges. In this process, topology shows potential load path and design solution that are used to extract and define the functional requirements of the structure. A design concept is finally developed with the physical interpretation based on functionality. The application of the process is illustrated on a simple example and on the flat pressurized plate presented in chapter two.

Chapter four discusses the application of the new design process on an aircraft pressure bulkhead. Each step of the process is applied and different design concepts are suggested. It proves that the process is efficient to explore the design space while avoiding problems associated to direct topology interpretation.

To conclude, the results obtained in each chapter are synthetized and the contribution of this work to the field of topology optimization based design is discussed. Finally, a discussion concerning future work inspired from this research is presented.

CHAPTER 1 LITERATURE REVIEW

This chapter first presents an overview of the topology optimization design process. It then summarizes the theoretical background of topology optimization. A review of two successful application of the design process in industry follows. In order to understand the case studied in this thesis, and introduction to aircraft pressure bulkheads is also presented. The discussion explains how the bulkhead can be idealized into a pressurized stiffened plate. Therefore, a critical review of literature concerning optimal stiffening of plate is conducted. A synthesis of the findings is finally presented and two research questions are developed.

1.1 Topology optimization design process

Figure 1.1 presents a conceptual comparison of the classic and the topology optimization based process for the design of structures. The difference between the two approach lies in the method used to generate the initial concept. This first design is typically obtained based on the experience and engineering judgment. This subjectivity can be removed by using topology optimization as it allows the visualization of optimal material placement based on mechanical criterion such as strength and stiffness requirements. It provides great insight of what the initial design should look like in the conceptual phase. Both design process are then taking the initial design as a baseline to perform analysis and optimization in order to meet all design requirements in the detailed phase. This topology design process was first suggested by Olhoff et al. (1991).

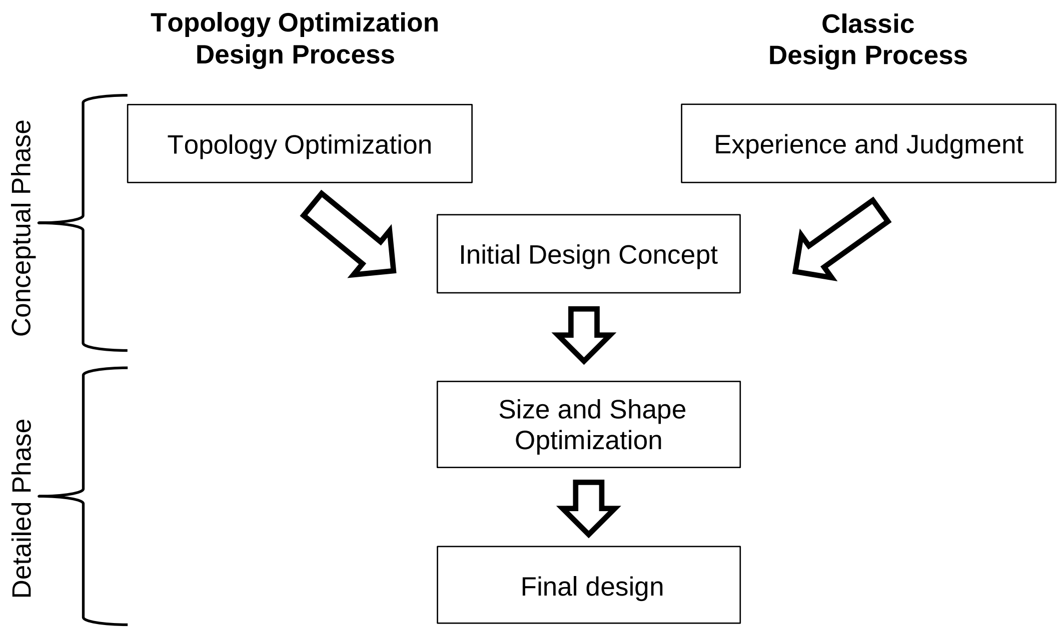


Figure 1.1 : Topology optimization role in the design process

The advantage of the topology optimization process lies in the generation of the initial design, which can be closer to a final design and hence reduce the number of design iterations. It allows exploring the design space without preconceived ideas. Different configurations can be explored rapidly and the most promising can be selected. This tool allows acquiring great knowledge in the conceptual phase of the design as illustrated by Figure 1.2. This early acquisition of information has high value because it is where design freedom is maximal and innovation can occur at minimal cost. This freedom is not present in the detailed design phase and only minor improvements can be obtained by typical optimization methods. The quality of the initial design therefore plays a major role in the final performance. The exploration of the design space by using topology optimization in the conceptual phase also decreases the risk of having to go through several iterations in the design cycle and therefore reduce design cycle time.

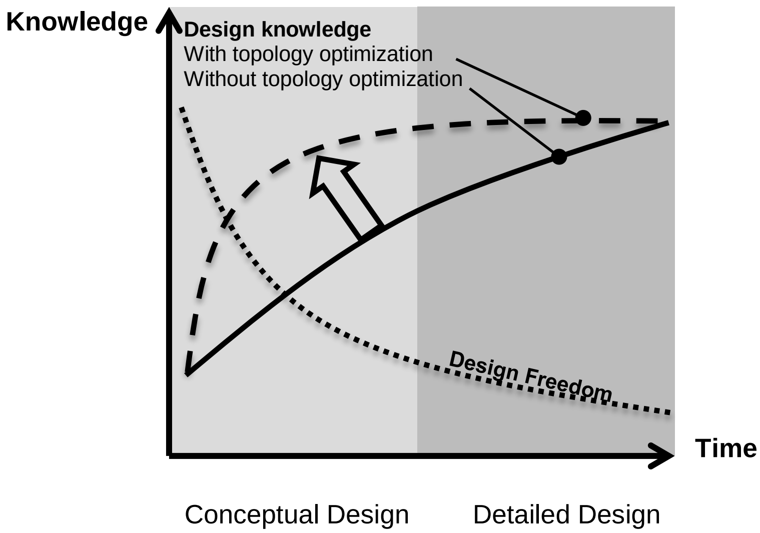


Figure 1.2 : Advantage of using topology optimization in the design process

1.2 Topology Optimization background

This section presents and discusses the theory behind the topology optimization method used in this thesis. It also discusses its typical application to structural design problems in order to familiarize the reader with this method.

Structural optimization is commonly used to optimize the size and shapes of components (Figure 1.3). For example, the thickness of a panel and its curvature can be optimized to minimize the mass while respecting maximum stress and displacement constraint. These types of optimization are performed on an existing design and cannot modify the structure by adding holes or structural members for example. This is where the structural topology optimization methods can be used. It can be described as a method that optimizes the distribution of material in a given design space. It is generally used to visualize optimal load distribution in a structure and generate innovative design concept.

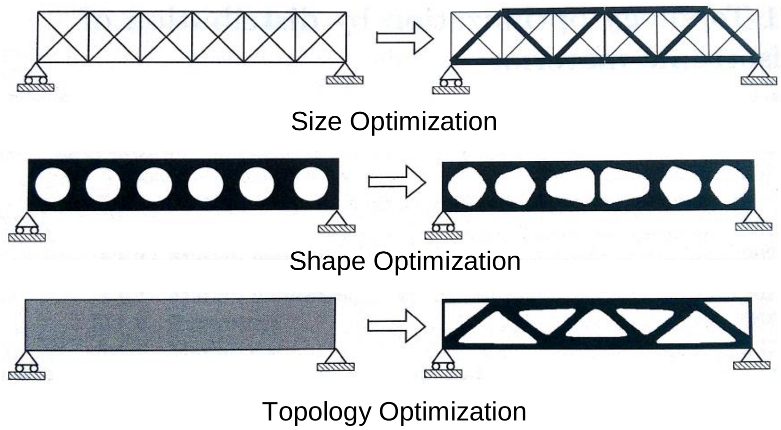


Figure 1.3 : Types of structural optimization (adapted from Bendsoe and Sigmund (2004))

Topology optimization is a broad research subject and different methods were developed to optimize material placement in a design space. An extensive review of the different approaches and their particularity can be found in the literature (Deaton and Grandhi 2013; Hans and Niels 2001; Sigmund and Maute 2013). However, one method is currently used and accepted by most of the research community and is now implemented in several commercial softwares such as Optistruct, Tosca and Genesys: it is the **S**olid **I**sotropic **M**aterial with **P**enalization (SIMP) method, also called the density method. This thesis uses the Optistruct solver from the Altair Hyperworks suite to perform all topology optimization and finite element analysis. This tool was selected for its availability and for its previous success in industrial applications. In order to use it efficiently, it is important to understand the theory behind this approach.

1.2.1 SIMP or density method

The design space where material can take place is discretized by the finite element method (FEM). The problem consists of finding which elements should represent material and which should not. This is also called a 0-1 problem or an Isotropic-Solid or Empty topology according to the terminology presented by Rozvany (2001). This discrete problem results in 2^N possibilities where N is the number of elements. The evaluation of all these possibilities is computationally prohibitive and thus optimization techniques are used. Optimization algorithms are more efficient at solving continuous design variable and response because they can use a gradient method that can quickly converge towards the objective. For that reason, the discrete topology design problem is relaxed into a continuous design problem. This is done by assigning a density design variable

(ρ) to each element that can take value between zero and one where zero represents absence of material and one represents presence of material. The density is directly factoring the element stiffness matrix ($\mathbf{K}$) to simulate material existence with the adjusted stiffness matrix ($\overline{\mathbf{K}}$). Therefore, the finite element mesh is constant throughout the optimization and the visualization of the density distribution simulates optimal material placement.

This continuous design variable can result in intermediate density which has no physical meaning since intermediate material does not exist. In order to force the density design variables towards discrete values (0 and 1), a penalization power (p) is introduced. This results into what is called the SIMP material interpolation scheme (Equation 1). The penalization takes value above one (typically between 2 and 5) which increase the cost of intermediate density on the objective function and naturally push the design variable towards discrete value.

$$\begin{gathered}\overline{\mathbf{K}}(\rho) = \rho^{p}\mathbf{K} \\ 0 < \rho \leq 1.0, \qquad p > 1.0\end{gathered} \tag{1}$$

The introduction of this penalization makes the optimization problem non-convex which means that there are several different local optimums in the solution space. It is therefore important to keep in mind that the result of the optimization is not necessarily the global optimum of the design space.

1.2.2 Typical topology optimization setup

Model: Design Space, loading and boundary conditions

The first step in order to perform a topology optimization is to model the design space and define the **loading** and **boundary conditions**. Figure 1.4 illustrates a simple topology optimization model for the design of a bridge. The road and the supports of the bridge are represented by **non-design space** where elements density is not variable. The zones where structural members of the bridge can take place are represented by variable density elements that define the **design space**. The model is loaded by a uniformly distributed load representing the weight of the vehicles and constrained at two locations representing the boundary conditions of the bridge.

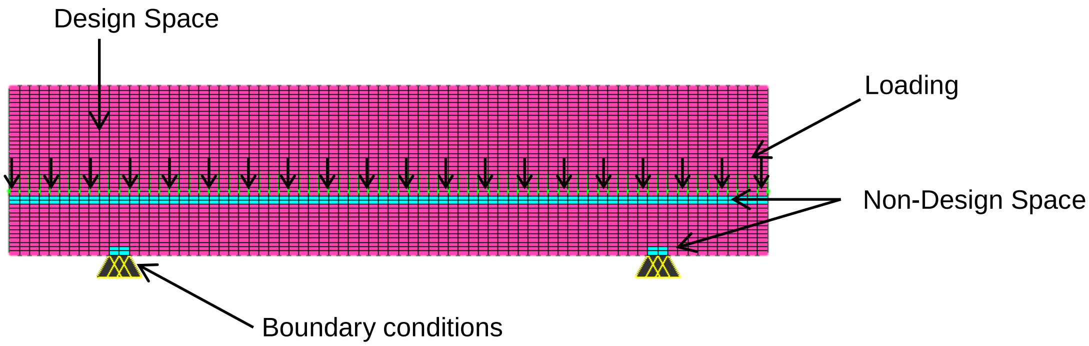


Figure 1.4 : Example of bridge model for a topology optimisation problem[1]

1.2.2.1 Optimization problem

The topology optimization problem is defined like any optimization problem (Equation 2). The values of the **design variables** vector (**x**) are optimized in order to minimize an **objective** function ($f(\mathbf{x})$) while respecting one or multiple **constraints** ($g_i(\mathbf{x})$).

$$\begin{gathered} \min f(\mathbf{x}) \\ subject\ to\colon g_i(\mathbf{x}) \leq 0 \qquad j = 1, \dots, m \end{gathered} \tag{2}$$

It is possible to use many optimization responses as an objective or constraints. The typical topology optimization problem formulations are given in Table 1.1.

Table 1.1 : Typical topology optimization problem formulation

Formulation	**Objective**	**Constraint**
A	Minimize compliance (Strain energy)	Volume/Volume fraction (or Mass)
B	Minimize volume/mass	Maximum Displacement
C	Minimize volume/mass	Maximum Global Stress
D	Minimize volume/mass	Minimum Buckling factor (1.0)

The original and most commonly used formulation is the minimization of **compliance** (strain energy) for a constrained volume **(formulation A)**. In other words, the stiffness of the structure is maximized for a fixed target volume. Multiple load cases can be handled by using a weighted average of the compliance associated to each load case. This formulation allows visualizing

[1] Adapted from Optistruct's user guide (Altair Engineering 2011)

optimal material placement in the design space. The volume selected can be directly related to the target design volume or it can also be fixed to a fraction of the total design space volume (volume fraction (VF)). Volume fractions between 20% and 30% are generally used to visualize the optimal material placement. This optimization formulation is not directly applicable to typical engineering design constraint such as stress, buckling and displacement. However, the concepts obtained when maximizing stiffness generally perform well with these constraints once interpreted (Schramm et al. 2004).

Other formulations are available in order to pose the topology optimization problem with more realistic engineering constraints. For example, the mass of the design can be minimized for a constrained maximum **displacement (formulation B)**. This constraint can work efficiently but it is somewhat similar to the compliance objective as the stiffness is directly driving the displacement. This formulation has the advantage of not having to select a volume fraction since it is minimized. It is however limited when used for a pressure load case because the displacement of each node is important which creates a problem with a large number of variables and constraints. It results in convergence problem and that does not result in a discrete structure.

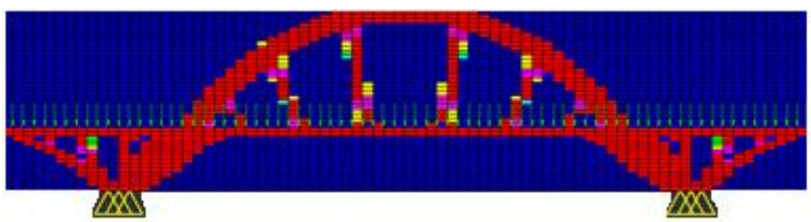
The minimization of mass for a maximum **stress** constraint **(formulation C)** can also be used. The advantage of this formulation is that it is typical of a real engineering design problem. However, it is important to be aware that the stress constraint is a global value that accounts for the whole design space. The existence of stress is conditional to the existence of material which is called the singularity problem. Other problem associated to local stress concentration and non-linearity of the stress response also makes it challenging to implement efficiently this response in the SIMP method. Several different approaches exist (Le et al. 2010) and the technique used in Optistruct is unknown. The general nature of the global stress constraint makes it comparable to the volume fraction constraint since the effect of the value of the constraint is not straightforward.

Topology optimization with **buckling** constraint **(formulation D**) is also feasible but is also very limited. The buckling factor associated to low-density zones may be very low since these zones have very low stiffness. It is therefore necessary to filter these zones from the buckling response which is challenging and only implemented for shell structures with non-zero minimum thickness (Zhou 2004).

These different approaches where tested on simplified cases representing the pressure bulkhead and the minimization of compliance for a constrained volume (formulation A) proved to be the most reliable to generate discrete topology results. Other response and objectives can be used but the user must be careful concerning their respective limitations for their specific problem.

1.2.2.2 Post-Processing

The post processing of a topology optimization consists of visualizing the element density distribution (Figure 1.5). This can be done by visualizing a density **contour plot** where high and low density elements are displayed in different colors. **Iso-plot** can also be used for 3D models to visualize elements above a specified density threshold. It can leave the user with the impression that topology removes elements from the model but it is important to remember that it is only a visualization.



Density Contour Plot
(Red: High Density. Blue: LowDensity)

Figure 1.5 : Typical example of topology optimization post-processing

1.2.3 Checkerboarding and mesh dependency

The apparition of checkerboard pattern in the density result is a known problem of the density method (Figure 1.6). It is associated to the finite element discretization where a checkerboard pattern results in an artificially stiffer design. The problem can be avoided by using a density filter or by using quadratic element formulation.

The density topology optimization problem is also known to be mesh sensitive since a different layout can be obtained for different mesh-size. This is due to the non-existence of solution of the density topology optimization problem. In other words, the introduction of more holes for a same volume will generally decrease the objective function (Sigmund and Petersson 1998). This problem is generally overcome by using different types of density filters. Optistruct filters the gradient of the density to avoid mesh dependency while controlling the minimum size of the members formed (Zhou et al. 2001).

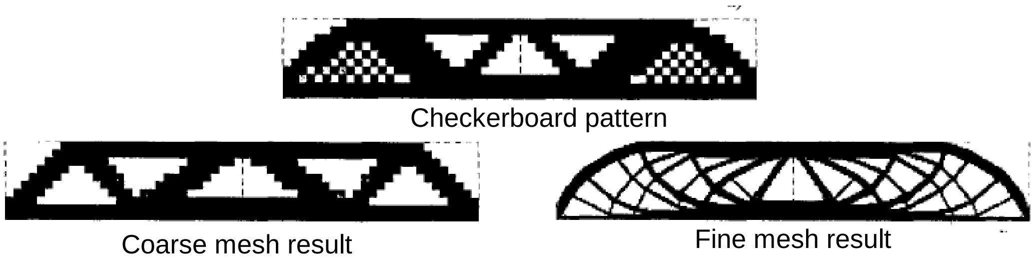


Figure 1.6 : Checkerboard and mesh-dependency problem[2]

1.2.4 Manufacturing constraints

The industrial use of topology optimization encouraged the development of manufacturing constraints as some concepts generated would be impossible or too costly to be manufactured. Optistruct offers several of them which can be used to force the topology to give more manufacturable results. They can be used to obtain topologies that are more manufacturable with typical material removal process, extrusion and casting process. Additive approaches can also be used to manufacture more complex topologies.

Minimum and maximum member size control

The minimum member size constraint (MINDIM) penalizes the formation of members smaller than wanted diameter (Zhou et al. 2001). The use of this parameter is highly recommended by the Optistruct's user guide as it helps obtaining more discrete and manufacturable topologies. As discussed earlier, this filter also avoids checkerboard and mesh dependency problem. However, the value of this constraint is somewhat dependent of mesh size since elements are used to apply the constraint on diameter.

The maximum member size constraint (MAXDIM) can be used along MINDIM in order to penalize the formation of members larger than a specified diameter.

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[2] Adapted from Sigmund and Petersson (1998)

It is also important to mention that it is possible to obtain members that violate these constraints if these are important for the objective.

Extrusion, Draw and pattern repetition constraints

Optistruct also offers extrusion and draw constraints for 3D design space. These constraints can be used to force a draw direction for casting parts or force a constant cross section for extrusions. Finally, pattern repetition constraints allow specifying various symmetry constraints.

1.2.5 Thickness Optimization (Free-Size)

Continuous thickness optimization (called Free-Size in Optistruct) is an alternative to topology optimization for shell structures. The density design variable is replaced by the thickness of each elements and no penalization power is used. This gives more design freedom since intermediate densities are not forced towards minimum or maximum values. However, problems where shell sustain bending load have an implicit penalization power like for the topology problem since the bending stiffness is proportional to the cube of the thickness.

The main difference between topology and free-size optimization is that topology result in discrete truss-like structures and free-size gives more continuous material distribution (Figure 1.7). Both type of designs are defendable and Cervellera et al. (2005) showed in an example that a beam web designed with free-size optimization was lighter than one designed with topology for high stiffness requirements. Free-size is used extensively for the design of composite material since it allows optimizing ply orientation, thickness and stacking sequence. However, only metallic structures are considered in this thesis and free-size is only used as an alternative to topology optimization on shell structures.

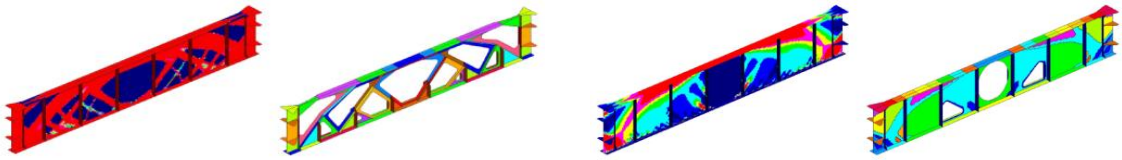


Figure 1.7 : Conceptual comparison of free-size and topology optimization [3]

1.3 Industrial applications

The availability of topology optimization in commercial softwares makes it usable for industrial application and this explains its rising popularity. Two industrial successes are briefly presented in this section. It shows the typical steps of the design process on real case studies and highlights the potential performance improvement. These studies are used as a basis to explore the use for topology optimization for the design of the pressure bulkhead.

1.3.1 Wing leading edge rib for Airbus A380

Airbus realized significant weight savings by using topology optimization for the design of the leading edge ribs of the A380 (Krog et al. 2002). The ribs are sustaining discrete loading coming from the actuators of wing slats along with aerodynamic loading. These loads are oriented in the plane of the 2D design domain. The optimization software Optistruct from the Altair Hyperworks suite was used to perform the whole design (Figure 1.8). The topology was found to be sensitive to loading, boundary conditions and to the formulation of the optimization problem (objective and constraints). The selected objective was finally to minimize compliance (maximization of stiffness) for a constrained volume. The topology resulted in a truss structure (discrete connected members). An interpretation involving engineering knowledge and experience allowed defining a size and shape optimization model to minimize the mass of the concept for typical stress and

[3] Adapted from Cervellera et al. (2005)

displacement constraints. The final design resulted in weight savings compared to the typical design approach.

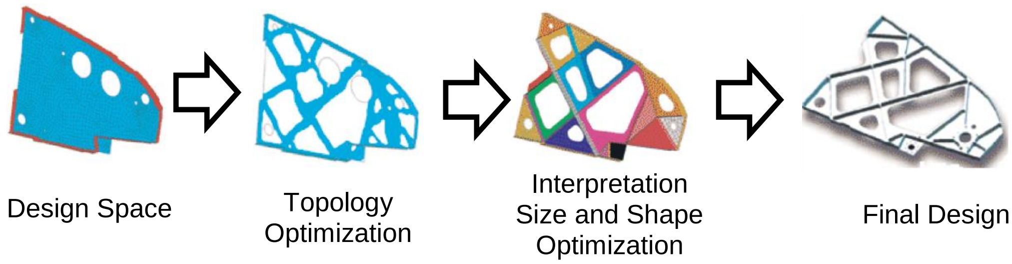


Figure 1.8 : Airbus A380 wing leading edge rib design

1.3.2 Chinook helicopter floor beam redesign

Boeing engineers also explored the application of topology optimization design process for the redesign of a chinook helicopter floor beam (Fitzwater et al. 2008; Hunter 2006). Once again, the two dimensional design space was mainly loaded in its plane. They also used Optistruct to perform all steps of the redesign (Figure 1.9). Topology optimization was used to visualize the optimal material placement. The objective was to minimize compliance for a constrained target mass. The author recommends doing several topology optimizations to get confident with load path and sensitivity. The result also consisted of a truss design concept. The interpretation along with a size and shape model was then defined with concerns for manufacturing. The interpreted design is then optimized to minimize weight for stress, displacement and buckling constraints. The optimized design was finally analyzed and tested for fatigue and fail-safe concerns. Weight savings of around 15% were achieved.

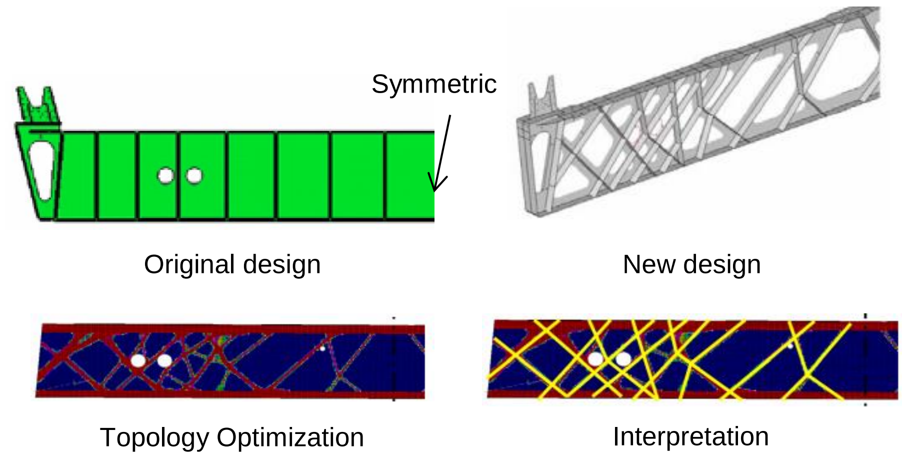


Figure 1.9 : Chinook helicopter floor beam redesign

Both of the studies identified challenges associated to the generation of topology because of the sensitivity of the result to optimization setup, loading and boundary conditions. Also, the interpretation of the topology layout required engineering input but no guidelines or methodology were provided.

1.4 Introduction to aircraft pressure bulkheads

The cabin of an aircraft needs to be pressurized as it flies at high altitude where the atmospheric pressure is too low to ensure normal breathing. The pressure differential between the cabin and the exterior is sustained by the aircraft structure. In other words, the aircraft fuselage acts as a pressure vessel. This pressure vessel has to be sealed by what is called pressure bulkheads. These pressure bulkheads are normally located in the rear fuselage, forward of the cockpit and at wing junctions. Figure 1.10 presents a detailed view of a typical rear pressure bulkhead along with a visualization of the location of these structures.

If the aircraft interior is idealized as a pressure tank, the natural shape of the ends can take the form of a dome or a flat stiffened panel. The dome is a more efficient structure under pressure but the flat stiffened panel is generally preferred for smaller aircraft. This is because a trade-off is made between structural efficiency of the bulkhead and the space gained for the installation of systems in the aft fuselage. Small aircrafts need to have as many systems as the large carriers and using dome bulkhead could result in an extension of the total fuselage length which also has a significant impact on aircraft total weight and drag. The space acquired can also be useful to carry more fuel and extend the range of a high performance business aircraft. Therefore, the rear pressure bulkhead considered consists of a flat assembly of skin and stiffeners.

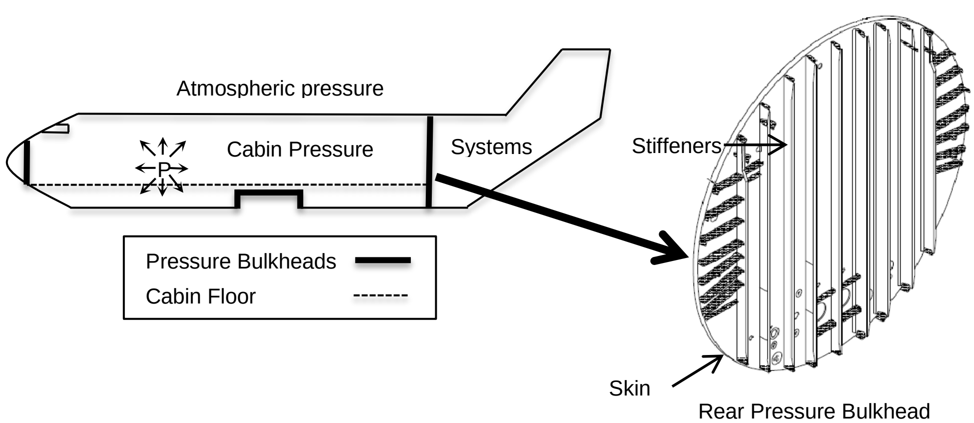


Figure 1.10 : Introduction to aircraft pressure bulkheads[4]

[4] Image on the right adapted from Bombardier Challenger 605 maintenance manual

One of the main differences between this design case and the industrial case studies presented is that the load is perpendicular (out-of-plane) to the design space plane instead of being in its plane. This means that the structure is mainly loaded in bending instead of being loaded in tension, compression or shear. There are no industrial case study considering such loading and the closest application was found in papers studying optimal plate stiffening.

The design of a flat bulkhead can be idealized as the design of the stiffening of a flat pressurized plate. This is typically done by adding straight and equally spaced stiffeners on the plate in order to provide appropriate support to the skin. It also allows controlling the dimensions of the bay formed between stiffeners. This stiffening solution may not be optimal and the topology optimization design process can be used to explore new concepts.

1.5 Plate stiffening using topology optimization

Application of topology optimization for the optimal stiffening of plate has been explored in several studies.

Lam and Santhikumar (2003) presented a study where the thickness of a plate is optimized in a first step to determine stiffener placement. As a reminder, the thickness optimization is similar to topology optimization when the structure is mainly loaded in bending which is the case in this study. Standardized stiffeners are then added to the plate and a comparison is made with a plate of uniform thickness with an equivalent volume. The maximum displacement is used as the comparison criteria. This innovative process is close to the topology optimization design process described earlier. However, there is no sizing optimization considering typical design constraints such as stress and displacement. Moreover, the study considers discrete loading and boundary condition and its applicability to pressure load remains unknown. Finally, the uniform thickness plate is not an adequate comparison basis since a stiffened panel is much more efficient.

Afonso et al. (2005) also proposed a process for the stiffening of plates using topology optimization to determine optimal stiffener position. Stiffeners are placed where high density elements are obtained. A sizing optimization is then performed on the interpeted model in order to obtain the optimal height of the stiffeners. The objective of the optimization is to minimize the compliance (strain energy) of the structure. This is once again far from typical engineering problems where mass is minimized for stress and displacement constraints. The examples presented also does not consider pressure loading. Finally, the comparison of performance is still made with a uniform thickness plate.

In summary, the application of topology optimization for pressure loading is an active research subject on various types of structures. However, its applicability to find the optimal stiffening of a flat plate under pressure has not been explored in a complete case study (from concept to sizing) according to the review performed. Moreover, the studies reviewed do not consider realistic constraints such as stress and displacement when interpreting and sizing stiffeners. Finally, the comparison to a uniform thickness plate is not representative of a stiffened plate design that could be obtained without topology optimization. Other studies were found but they all had similar limitations (Ansola et al. 2004; Luo and Gea 1998; Stok and Mihelic 1996).

1.6 Synthesis

The literature review showed that the topology design process can result in performance improvement as it was the case for representative industrial case studies. The studies also highlighted challenges associated to the generation and interpretation of topology but did not propose a systematic methodology to address them. Moreover, application of the topology design process for the optimal stiffening of a pressure bulkhead has not been explored in industry according to our knowledge.

The bulkhead can be visualized as a flat pressurized stiffened panel and a review on optimal plate stiffening using topology optimization was also conducted. Unfortunately, the pressure load case was not considered in the researches and the sizing performed did not account for typical constraints such as stress or displacement. Moreover, the comparison of result with a uniform thickness plates is not representative of true performance improvement compared to a typical stiffened panel.

As a reminder, the objective of the present project is to explore the use of topology optimization for the design of a flat pressure bulkhead and develop a design process from the acquired knowledge. Based on the information presented in the literature review, this objective can be translated into the following two research questions.

Research questions

1. How does the topology optimization design process performs compared to a typical design for flat pressurized stiffened plates?
2. How to address the identified challenges of the actual topology optimization design process?

The hypothesis and the methodology used to address them are also considered:

Hypothesis

1. Topology optimization will improve product performance compared to a typical design.
2. Combining topology optimization and axiomatic design principles can address the challenges associated to the generation and the interpretation of design concepts.

Methodology

1. Study a simplified pressurized plate and compare the results with a typical design to identify challenges and estimate performance improvement. (Presented in Chapter 2)
2. Develop a design process using Axiomatic Design to support topology optimization and apply it to the pressure bulkhead design case for validation (Presented in Chapter 3 and Chapter 4)

CHAPTER 2 ARTICLE 1: CHALLENGES OF USING TOPOLOGY OPTIMIZATION FOR THE DESIGN OF PRESSURIZED STIFFENED PANELS

A. Dugré, A. Vadean, J. Chaussée (2014). Submitted in the "Structural and Multidisciplinary Optimization" journal on July 2nd 2014.

2.1 Presentation

The bulkhead is a complex structure and it is first simplified in order to answer to the first research question defined after reviewing the literature. How does the topology optimization design process performs compared to a typical design for flat pressurized plates?

The bulkhead is therefore simplified as a flat and simply supported pressurized rectangular plate. The dimensions and constraints used are inspired from the bulkhead in order to use realistic order of magnitude and maintain a physical sense of the values used.

This case study allows focusing on the particularity of the out-of plane pressure loading associated to the bulkhead design case. It aims at filling the knowledge gap identified concerning optimal stiffening of pressurised plates using topology optimization. Therefore, a pressurized stiffened plate is studied and the performance of the topology designs is compared with a typical and intuitive design using design constraints such as stress and displacement. This application of the topology design process has never been explored before which encouraged writing the journal paper presented in this chapter. The paper submitted to *Structural and Multidisciplinary Optimization* aims at presenting and discussing the challenges associated to the use of density (SIMP) topology optimization for the stiffening of flat pressurized plates. It represents an important realization of this master thesis project since it is the synthesis of many findings concerning this type of structures.

The knowledge acquired and the challenges identified throughout this application of the topology design process are used to define the improved design process presented in Chapter 3.

2.2 Abstract

Topology optimization has been successfully used in several case studies in aerospace and automotive industries to generate innovative design concepts that lead to weight savings. This motivates the exploration of this new approach for the design of an aircraft flat pressure bulkhead. However, no studies were conducted on this type of structure. Therefore, this paper presents and discusses the challenges associated to the design of flat pressurized plate using topology optimization (SIMP (**S**olid **I**sotropic **M**aterial with **P**enalization) method). A simply supported rectangular plate is used as the design case and a typical layout is defined as a comparison basis. The mass of the interpreted design concepts are obtained with a simplified sizing approach taking into consideration stress and displacement constraints. Results show that the topology layout is not unique as is sensitive to optimization parameters. Moreover, the interpretation of the layout is challenging as they are driven by complex interactions. Finally, the performance of the topology design concept is at most comparable with the typical layout and no significant improvement is obtained. The study highlights the importance of performing an extensive topology study in order to better understand the behavior of the design before creating a concept.

Keywords: stiffened plates, topology optimization, pressure, bulkhead

2.3 Introduction

Structural design process typically consists of creating an initial design based on experience and optimizing it to obtain the desired performance target. Relatively recent methods such as topology optimization implemented in commercial software can improve this process. This technology shows optimal material placement in a design space based on load and boundary conditions. It helps exploring the design space and results in innovative initial design. The concept is then optimized as usual and the final performance is improved compared to a typical design. This design process was first suggested by Olhoff et al. (1991). Since then, this approach was successfully applied in industries such as automotive and aerospace. Krog et al. (2002) presented an application of this approach for the design of aircraft leading edge rib where significant weight saving was obtained. Other success stories can be found such as the one presented by Fitzwater et al. (2008) that reduced the weight of a helicopter floor beam. These two applications had the common characteristic of having a flat design space mainly loaded in its plane.

Encouraged by these industrial realizations, this paper studies the application of the topology design process on a two-dimensional aircraft structure: a flat pressure bulkhead. This structure seals the pressure differential between the cabin and the atmosphere and typically consists of an assembly of thin skin panels supported by stiffeners (Figure 2.1). It is a complex structure mainly loaded out-of its plane by differential pressure but that also sustains in-plane loading coming from fuselage and local structural connections. As a first step towards evaluating the potential of topology optimization process for the design of a bulkhead, a simplified design case is explored in this paper. As a matter, the bulkhead is represented by a simply supported rectangular pressurized plate. This allows isolating the effect of out-of-plane pressure which is dominant. Therefore, the objective of the paper is to discuss the challenges associated to the design of flat pressurized stiffened panel using the topology optimization process.

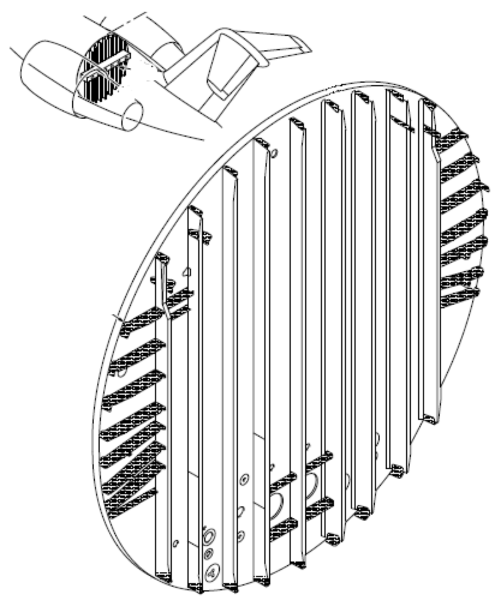


Figure 2.1 : Example of flat bulkhead with stiffeners[5]

Optimal layout has been an active research subject since the beginning of numerical topology optimization marked by a landmark paper from Bendsoe and Kikuchi (1988). Since then, several

[5] Image adapted from Bombardier Challenger 605 maintenance manual

techniques have been developed such as the SIMP (**S**olid **I**sotropic **M**aterial with **P**enalization) method (Rozvany et al. 1992) which has become popular and that is implemented in commercial softwares. The reader is referred to review papers for details concerning topology optimization methods (Deaton and Grandhi 2013; Sigmund and Maute 2013). Stiffening of a plate with discrete loading has been explored by Lam and Santhikumar (2003) who used an optimal layout approach to determine stiffener placement. The displacement of the stiffened design was compared to an equivalent thickness plate, showing performance improvement. Afonso et al. (2005) proposed a similar process where the position of stiffening ribs is first determined using topology optimization. Rib dimensions are then sized in order to minimize compliance of a plate with discrete loading and boundary conditions. The result also showed performance improvements compared to a uniform thickness plate. These studies are limited as they do not perform a complete interpretation and sizing of the topology concept, taking into account practical design constraints such as manufacturing, stress and displacement. Moreover, the comparison with a uniform thickness plate is not representative of a typical stiffened plate design that could be obtained without using topology optimization. Other studies concerning optimal plate stiffening with similar limitations can be found (Ansola et al. 2004; Luo and Gea 1998; Stok and Mihelic 1996). There is therefore a clear need for a case study presenting the application of current topology optimization technology for the design of pressurized stiffened panel.

This paper aims at filling this gap by presenting a complete case study using SIMP topology optimization available in commercial software Optistruct from the Altair Hyperworks suite. This software is selected because it has been used in the two successful industrial case studies previously mentioned and it is ready for application to large scale problems. The topology design process is applied on a design case and the performance of the design concepts is compared with a typical stiffened panel design. The results obtained highlight challenges arising throughout the process and can be used as a guideline for any future similar application. They can also be used as a reference for future work on topology optimization techniques for pressurized stiffened plates.

The design case, the design process and the mass estimation approach are first defined. The typical layout used as a baseline for comparison is then presented. The challenges of generating and interpreting a stiffener layout using topology optimization follow. Finally, the performances of the layouts are compared.

2.4 Methodology

The design case used to explore the stiffening of pressurized panels is defined in this section. The topology design process is then presented. Finally, the mass estimation methodology used throughout this paper is described.

2.4.1 Design Case

The aircraft pressure bulkhead is simplified as the rectangular design case presented in Figure 2.2. The simple support conservatively approximates a design where the impacts of the surrounding structural elements (such as floor, intercostal, etc.) are neglected. The design space dimensions are inspired from those encountered in a large business aircraft. The minimum skin thickness is set to 1.25 mm which is a classical value for pressure bulkhead web. The objective of the design is to minimize its mass while respecting stress and displacement constraints. Structural failure is not allowed and the magnitude of the pressure is inspired from the ultimate load case. In this study, this criterion is simplified by ensuring stress does not exceed its maximum value and that the maximum displacement at stiffener location does not exceed 1 percent of the longest dimension (Figure 2.2).

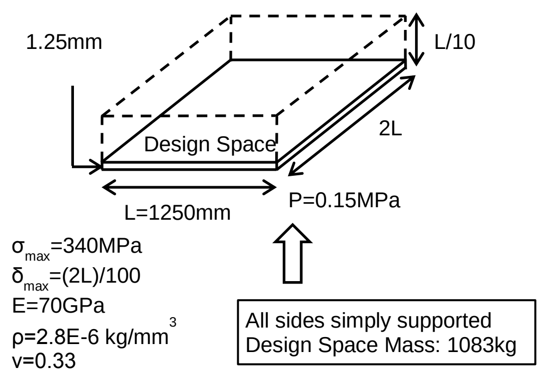


Figure 2.2 : Design case

The simplest solution to this design problem is a uniform thickness plate. In order to capture the effect of membrane stiffening, a non-linear geometric analysis is used to determine the thickness that minimizes mass while respecting the design constraints. A thickness of 13.5mm corresponding to a mass of 118kg is obtained to respect the maximum displacement constraint.

This design is obviously not the most efficient and the mass can be significantly reduced by adding stiffeners on the plate while diminishing its thickness.

2.4.2 Design Process

This simple design case contains an infinite number of solutions. This large solution space is reduced by using the topology optimization design process. This process is compared to the typical design process in Figure 2.3. The main difference between them is how the initial design concept is generated when starting from the same design space.

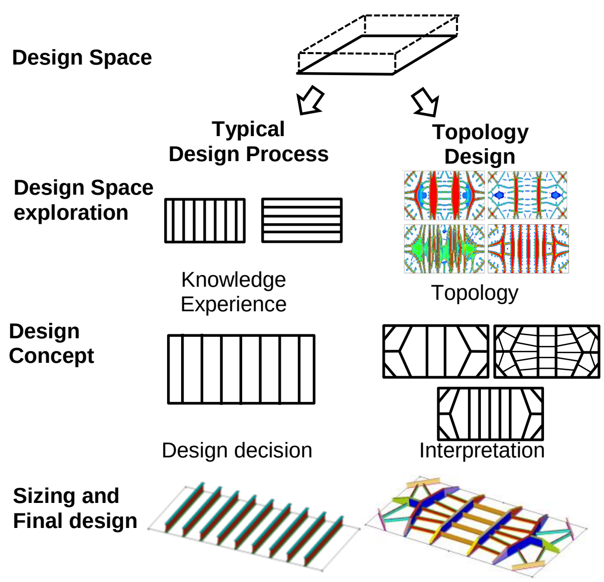


Figure 2.3 : Design process comparison

The typical design process uses engineering knowledge and experience to explore the design space and obtain a design concept. This intuitive approach implicitly considers many design constraints at the same time and experience plays a major role in creating good designs. The concept is then sized to obtain a final design. The baseline design is based on that process and is presented in section 2.5 of this paper.

The topology design process has a different approach to generate the design concept. The first step consists of exploring the design space using topology optimization. This first step can be challenging as it can lead to different layouts as discussed throughout section 2.6. The next step is the interpretation of the topology optimization results. It is somehow similar to the typical design process as it requires engineering knowledge and experience in order to understand the intent of the topology optimization result and transform it in a feasible design as discussed in section 2.7 of this paper. The performance of different layouts can be compared after the sizing step as shown in section 2.8.

2.4.3 Sizing and mass estimation

The sizing of a typical layout is usually done with analytical methods such as the ones available in Bruhn (1973) which is a reference for aerospace stress analysis. However, a finite element shell model is used to simplify the mass estimation and ensure coherence between design concepts. A geometric non-linear analysis is used to capture the membrane stiffening effect of the large deformation of the skin, bay between stiffeners. The sizing of the stiffeners and the skin are performed independently.

2.4.3.1 Stiffener Sizing

Depending on the magnitude and nature of the load, the type of stiffener attached to the skin panel can range from blade type (no free-flange) to I sections. This study considers I beam as they are efficient to sustain high bending load generated by the pressure on skin. Figure 2.4a presents a typical skin-stiffener assembly. The design studied has its stiffeners on the non-pressurized side which ensures no local buckling can occur in the free-flange since it sustain tensile load. Skin has a local pad-up to ensure thickness compatibility with bottom flange to allow proper fastener installation. It contributes to beam second moment of inertia (I) and lowers its centroid which makes the top flange the critical stress location for bending load.

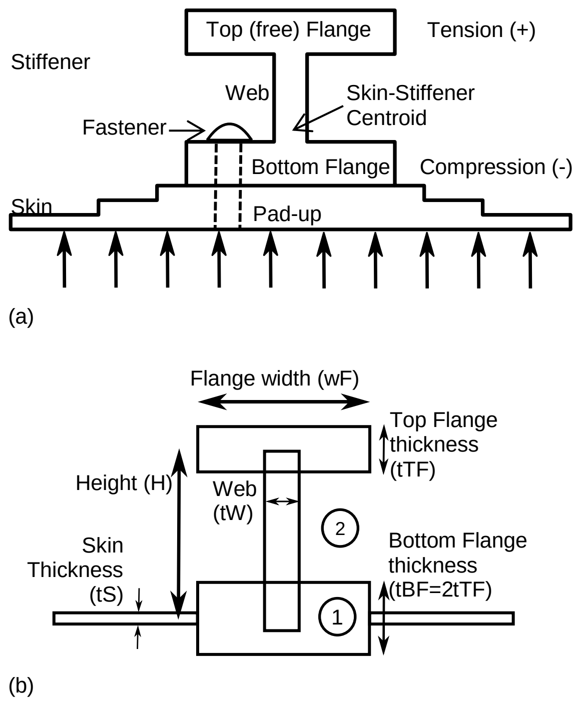


Figure 2.4 : Beam mass estimation: (a) Typical Skin-Stiffener assembly, (b) Simplified Shell Model

The simplified modelling aims at representing skin-stiffener inertia using shell elements (Figure 2.4b). The height of the beam is determined by the height of the modelized web. To account for the effect of skin on beam stiffness and centroid, the bottom flange shell thickness is fixed to twice the top flange value (1). This implies that a part of skin mass is included in the beam mass estimation. The thickness of the web in bending is determined to obtain an allowable buckling stress equal the maximum allowed stress using analytical plate buckling analysis (Bruhn 1973) (2). These rules simplify sizing and mass estimation of the stiffener for the layouts presented in this paper.

The non-linear analysis makes the use of typical size and shape optimisation challenging. Therefore, the sizing is performed by varying web height and flange section area. These two parameters have the most impact on beam inertia and are optimized to respect maximum stress (in the top flange) and displacement constraint while minimising mass. Flange area is optimized by keeping constant width and varying its thickness. The thicknesses are limited to a minimum value of 1.25 mm to account for typical manufacturing limitations. Using this approach, a beam with high loading will reach maximum allowable height and its flange area will be increased until respecting constraints. On the other hand, a lightly loaded beam will not necessarily use all allowable design space. In that case, its height will be maximized while using minimum thickness in order to respect constraints. This simplified approach does not necessarily lead to absolute mass minimum but it is sufficient to obtain a consistent comparison basis between designs.

2.4.3.2 Skin Sizing

The mass estimation of skin is independent of the stiffener sizing. Figure 2.5 presents a summary of the skin mass estimation approach. The maximum stress is typically located at the stiffener junction because of the clamping edge condition it provides to the bay (1). This stress concentration is typically reduced by gradually decreasing skin thickness between the pad-up towards the center of the bay (step). The non-linear membrane effect makes the design of this ramp complex and hence, it cannot be considered to estimate skin mass simply. Instead of estimating skin bay mass based on stress, a simple criterion limiting allowable membrane effect based on the aerospace structural handbook (Niu 1999) is used. This criterion simply states that the maximum displacement (δ) of a bay must not exceed five times its thickness (tS) (2).

This criterion ensures that the bay is supporting pressure load with a limited membrane stiffening effect which is required for typical aerospace designs. The mass estimation of bay is obtained by finding the thickness that respects this criterion on a simplified model where nodes are clamped at stiffener location (3). This provides a simple and general basis to capture and compare the effect of skin mass on any design concept.

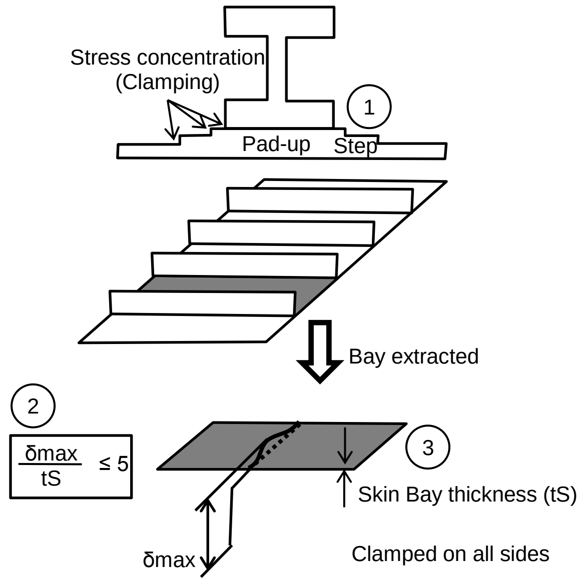


Figure 2.5 : Skin mass estimation

2.5 Typical design

2.5.1 Design philosophy

The design case presented in section 2.4.1 can be solved by using the typical design process where engineering knowledge and experience are used to generate an initial design concept. This typical layout is used as a comparison basis to evaluate the performance of the topology design process (Figure 2.6). The main function of the stiffeners is to support the deformation of the skin panel. A single stiffener is not sufficient as it results in large skin bay that still need support. This is why several beams are then placed at equal spacing (pitch). The constant spacing gives a balanced pressure redistribution that allows using the same dimensions for all beams and skin bay which simplifies design and manufacturing. The beams are aligned with the shortest dimension of the plate to have the smallest length and reduce bending load.

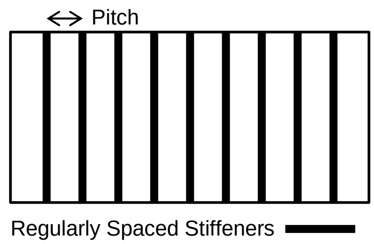


Figure 2.6 : Typical layout

The design variable of this stiffener layout is the stiffener pitch. This parameter controls the dimension of the bay which affects many responses such as the skin stress, displacement and buckling. The selection of pitch therefore implies a trade-off between skin and beam mass. Figure 2.7 presents the effect of varying the number of stiffeners on mass. It shows that total mass is reduced with more beams until reaching minimum skin thickness. According to the sizing methodology described in section 2.4.3, this corresponds to 9 equally spaced stiffeners for a minimum skin thickness of 1.25mm.

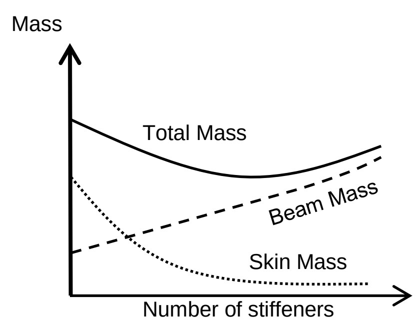


Figure 2.7 : Mass vs number of stiffener

2.5.2 Mass estimation

A model of the typical layout with 9 equally spaced beams is used to estimate the mass. Beams reach their maximum height while their width is set to approximately one third of this value. The maximum stress in top the flange is critical and maximum displacement is respected (Figure 2.8).This performance is used as a baseline for comparison with topology design.

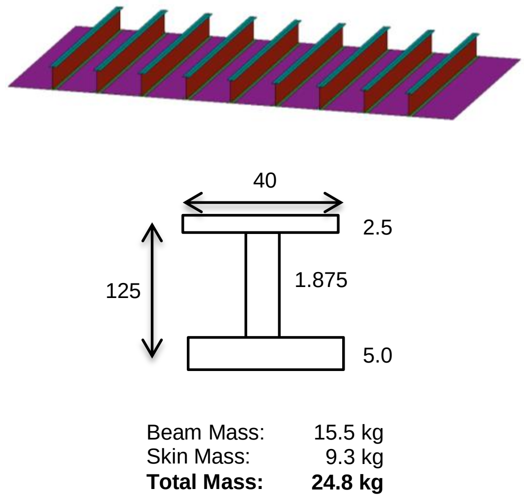


Figure 2.8 : Typical design mass estimation

2.6 Challenges of generating a topology layout

This section describes how topology optimization is used to generate stiffener layout in order to obtain design concepts. It first presents an overview of the SIMP topology optimization method. The effect of available optimization parameters on the layouts obtained is then studied. Finally, limitations of the typical implementation of topology optimization such as linear analysis and local optimum are discussed.

2.6.1 Optimization problem

2.6.1.1 SIMP density design variable

The commercial software Optistruct from the Altair Hyperworks suite has been used to perform this study. It is based on the widely accepted SIMP method also known as the density method. Moreover, it provides a variety of tools useful for the interpretation and sizing of the design. Its potential application to large scale problems and its success in several industrial case studies motivated its use.

The density method is based on a homogenous material with variable stiffness achieved by the interpolation scheme presented in Equation 2.1. A continuous density design variable (ρ) that ranges between 0 and 1 is assigned to each finite element of the design space. This density is directly affecting the element stiffness matrix ($\mathbf{K}$). The element therefore has an adjusted stiffness matrix ($\overline{\mathbf{K}}$) where low density represents low stiffness and simulates absence of material and high density represents the opposite. The low-density is usually limited to a minimum value to avoid ill-conditioning of the stiffness matrix. To eliminate intermediate density that don't have physical signification, a penalization power **(**p>1**)** is added to the density variable. This penalization forces the optimizer towards more extreme values (solid or void) in order to generate a more discrete structure.

$$\overline{\mathbf{K}}(\rho) = \rho^{p}\mathbf{K}$$

Equation 2.1 : SIMP material interpolation scheme

2.6.1.2 Design space definition and modelling

The density design variables need to be assigned to elements modelling the design space defined in section 2.4.1. This volume is represented by Mindlin shell elements, with a thickness corresponding to the maximum allowable stiffener height (125mm). A minimum thickness is specified based on the minimum skin thickness defined earlier (1.25mm). The optimization modifies the density variable assigned to each element to generate a stiffener with a rectangular cross section (Figure 2.9). This modelization represents a beam that is symmetric with respect to the skin plane which is not representative of the final design considering its attachment to the skin. This neglects the effect of skin on beam inertia but this limitation does not affect the search for optimal stiffener position. The modelization represents a beam by using very thick shell elements. This particular approach is necessary when using shell topology optimization. The behavior of such shell beam was evaluated and proved to be valid compared to beam elements. Finally, it is important to note that the typical layout with constant pitch is contained in this design space.

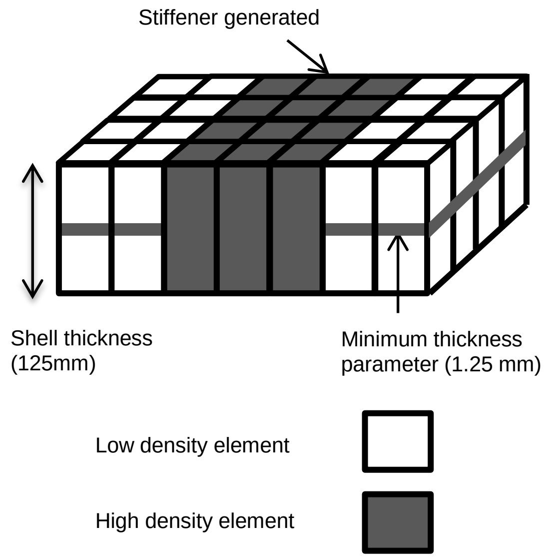


Figure 2.9 : Modelization of the design space

2.6.1.3 Objective selection

The typical optimization problem used for the density method is to minimize the compliance (maximize the stiffness) for a constrained amount of material (Bendsoe and Sigmund 2004). This amount of material can be represented by an absolute volume target or a volume fraction (VF) of the initial design space. This formulation is not representative of typical engineering design problems that are concerned by stress, displacement and buckling constraints. However, it can be efficiently used to visualize material placement and visualize optimal load path. Moreover, the stiff design suggested by topology using the minimize compliance objective is likely to perform well with constraints such as stress and displacement (Schramm et al. 2004).

The SIMP method also allows other formulation such as minimizing the mass for a constrained displacement which can be directly applied for the design case. However, this approach is not efficient for pressurized plates since the displacement constraint needs to be applied to all nodes inside the design domain. It results in an optimization problem with a large number of constraints and variables which brings convergence issues that prevent the generation of a discrete stiffener layout.

Finally, using stress constraint while minimizing mass is not an appropriate formulation for the design case since this global constraint does not properly capture the stress value in the stiffeners like a sizing model would do for an interpreted design concept.

In summary, the pressurized plate case poses a challenge towards using other objectives than the typical minimization of compliance. This problem is solved by Optistruct using a linear finite element analysis and a gradient based optimizer (Altair Engineering 2011).

2.6.2 Parameter effect

The topology optimization problem described above does not have a unique solution and the selection of optimization parameters affects the resulting layouts. In order to illustrate this, a baseline topology is first presented. The effect of volume fraction and the software capabilities in terms of manufacturing constraints are then presented as these parameters affect the most the layout obtained. The effect of other parameters such as mesh-size and minimum thickness is then discussed.

2.6.2.1 Baseline Topology

The baseline topology (Figure 2.10) has a mesh density of 100 per 200 linear plate elements corresponding to an element size of 12.5mm. A penalization power of 3 is used along with checkerboard filter to avoid the numerical issue related to linear element formulation. The volume fraction is set to 30% as a commonly used initial value. The contour plot shows a stiffening pattern that can be used to create a design concept. However, the layout can be significantly affected by optimization parameters.

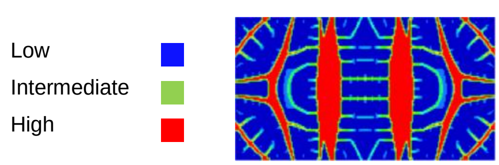


Figure 2.10 : Topology Baseline Layout

2.6.2.2 Effect of volume fraction

Volume fraction (VF) is an important parameter when minimizing compliance in topology optimization. In some cases, it can be selected by directly targeting the final design mass. However, in the case studied, the typical design mass (24.8kg) is very small compared to the design space mass (1083kg) which results in a very low target VF of less than 3 percent. This low value is not typically used for density topology optimization as Rozvany (2001) clearly mentions that **G**eneralized **S**hape **O**ptimization (topology optimization) is intended for high VF. Moreover, the VF response of the topology design space is not representative of a concept (interpreted) design as it does not account for the use of a different stiffener cross section that can achieve similar functionality with much lower volume fraction.

Instead of using a single volume fraction representing a target mass, the layout sensitivity to this parameter is observed for values between 5 to 50 percent (Figure 2.11). These VFs allow visualizing the optimal material placement, although the solution is not directly linked to engineering design constraints such as stress or displacement. The load path observed is then used to perform the interpretation step and obtain a meaningful final design.

The figure shows that the central portion is constantly stiffened by two stiffeners in the shortest direction of the plate but the remaining portion is stiffened in different ways for different VF. The low VF layouts (<15) do not show clear and constant stiffening pattern like the higher VF (>25). This load path sensitivity makes it difficult to decide which layout is the best as they are all local optimums and their true performance and behavior remains unknown until going through the interpretation and sizing step. The selection of volume fraction is therefore an important parameter to consider when generating stiffener layout on a pressurized plate.

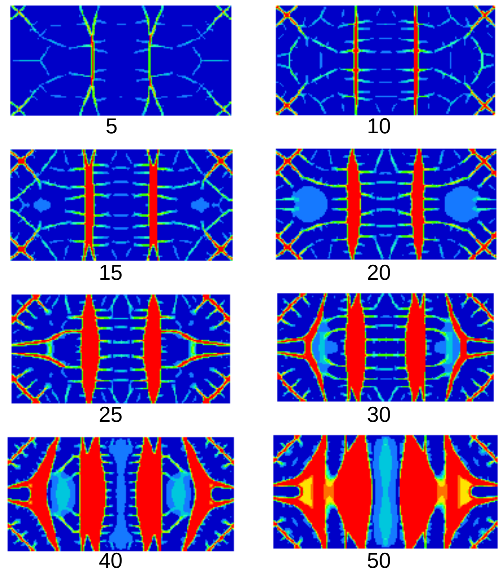


Figure 2.11 : Effect of volume fraction (VF)

2.6.2.3 Effect of manufacturing constraints

The solver (Optistruct) has specific manufacturing constraint capabilities that control the size of the members formed during the optimization which is a very interesting add-on to the method. Although these constraints are specific to this commercial implementation of the SIMP method, they can affect the topology significantly. The *minimum member size* (MINDIM) is a filter that penalizes the formation of small members by constraining their minimum diameter (Zhou et al. 2001). The use of this parameter is recommended to obtain discrete and manufacturable design concepts and is required when using other manufacturing constraints such as *maximum member size* (MAXDIM). The MAXDIM constraint penalizes the formation of members larger than specified.

It is important to note that both of these constraints are related to mesh size since elements are used to evaluate member diameter. The minimum allowable value for MINDIM is at least 2 times the average element size and at least two times MINDIM for MAXDIM. The baseline topology mesh size (12.5mm) therefore allows constraining the maximum member size to a minimum value of 50mm. This ensures that the stiffener generated have a width (50mm) smaller than their height (125mm) which is typical of a beam sustaining bending.

Figure 2.12 presents the effect of using these manufacturing constraints on the baseline layout. The MINDIM constraint has a small effect on the layout and load path as it is similar to the baseline. However, the MAXDIM constraint has a significant effect since large members are penalized and replaced by several smaller members. It shows that manufacturing constraints can also have a significant effect on the topology layout and load path. Finally, it is interesting to note that the central portion reminds us of the typical layout where stiffeners are placed in the short direction with a regular pitch.

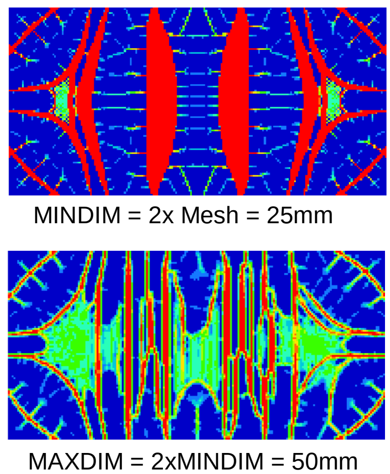


Figure 2.12 : Effect of member size constraints on layout

2.6.2.4 Other potential influences

There are other optimization parameters available when generating a topology layout. The effect of several of these parameters was studied but the results are not presented here because the layouts obtained were not significantly different from those already presented. However, selecting these parameters can be challenging and this is why their effects will be briefly discussed.

The use of a *quadratic mesh* avoids checkerboarding problem but does not have an important effect on the layout. A linear mesh is used as it is typically used in industry and is more suited to large scale problems. Although the density method is known to be sensitive to *mesh size* (Sigmund and Petersson 1998), the baseline layout is not affected by this parameter since no significantly different primary load path are formed.

The *ratio* of the minimum over the maximum shell thickness of the design was also explored. The topology obtained for large values of this ratio (>10%) were not resulting in a discrete layout since large zones of intermediate density were observed. The layout is also slightly sensitive for values below 10%. The design case has a very thin skin compared to stiffener height and this is why the smaller ratio of 1% is used.

The optimization of plate thickness (called free-size in Optistruct) was also explored as an alternative to using SIMP method to find optimal stiffener placement. In that case, a design variable is assigned to each element and no penalization is used. However, because of the bending nature of the problem, the thickness is naturally penalized since it has a cubic relation with bending stiffness. Although this methodology is not related to the SIMP approach, it can be used to visualize optimal thickness distribution and stiffener placement. Once again, the layouts obtained were similar to those presented earlier and no different load paths were suggested for this design case.

In summary, topology result is not unique and is sensitive to optimization parameters. This can be challenging as the designer needs to create a design concept based on a topology layout but at this stage he does not have sufficient information to make the correct decision.

2.6.3 Technical limitations of the commercial implementation of the SIMP method

The selection of optimization parameter is not the only challenge associated to the generation of a topology layout. The typical commercial implementation of the SIMP method also has technical limitations that can affect the generation of layouts. The linear finite elements analysis cannot model the membrane stiffening effect of a pressurized plate and the gradient optimizer cannot explore the design space completely as it converges to local optimums.

2.6.3.1 Linear Analysis

The typical implementation of the SIMP method uses a linear finite element analysis to evaluate the responses as it is the case in the software used. It cannot account for the non-linear membrane stiffening effect of thin pressurized plate that is present in the design case. Stegmann and Lund (2005) show that non-linearity in density topology optimization can affect the density result significantly for a simply supported plate with central load. This limitation prevents from evaluating the effect of the non-linear deformation on the layout obtained. However, it can be assumed that the deformation of low-density zones (corresponding to thin plates) is not realistic and this can affect the optimization as their compliance is overestimated. Moreover, the large deformation can introduce an overestimation of torsional load on the stiffeners formed during the optimization (Figure 2.13). This may wrongly create stiffeners with high torsional stiffness in the topology layout. However, the impact of non-linearity may be reduced by the formation of intermediate density stiffeners that generate smaller bay that are less affected by the membrane stiffening effect.

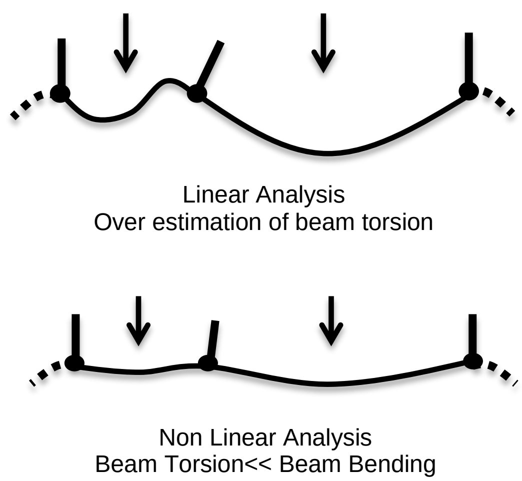


Figure 2.13 : Effect of linear analysis on beam torsion

2.6.3.2 Local Optimum

As mentioned earlier, the SIMP method uses a gradient optimization method that converges towards the nearest local optimum. This means that the SIMP method cannot completely explore the design space provided which means that it does not necessarily result in the best layout. For example, the typical layout presented in section 2.5 is a solution of the design space that is not naturally reached by the SIMP method.

Changing the initial value of the design variable can lead to other local optimum with a gradient optimizer. This would require modifying the initial density of the design variable but it is not a common practice. However, the effect of the starting point can be explored in a more conceptual fashion by locally modifying the boundary conditions of the design space. A minor discontinuity of the support can affect the initial compliance distribution which changes the progress of the optimization and the final layout significantly as presented in the example of Figure 2.14.

This figure shows the layout obtained when local out-of-plane support is introduced to one node inside the plate domain at typical design beam location. This additional support introduces a compliance concentration in the first iteration that changes the evolution of the optimization. Material is first placed near these discrete locations and these are gradually attached together to support the plate deformation. The result in the center portion of the plate is similar to the typical design (presented in section 2.5) and the layout obtained with the MAXDIM constraint. Thus, the result is very different from the baseline topology (Figure 2.10). This sensitivity to boundary conditions and the convergence to local optimums is therefore another challenging aspect when generating a stiffening layout using density topology optimization. The designer is exposed to local optimums and has no assurance that the result observed is the best that can be obtained from the design space provided.

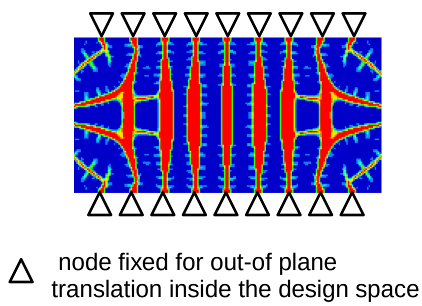


Figure 2.14 : Effect of local boundary conditions

2.7 Interpretation challenges

Interpreting the topology layout into a feasible design concept also involves challenges as this step is not straightforward and requires engineering judgement and knowledge. Since the topology optimization does not result in a unique solution, four representative layouts were specifically retained for the purpose of discussion as shown in Figure 2.15.

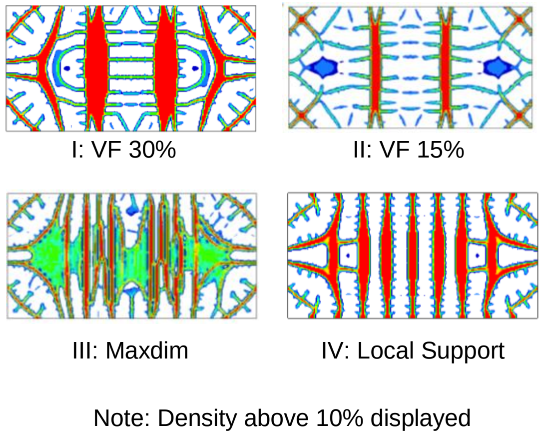


Figure 2.15 : Layout retained for interpretation discussion

2.7.1 Stiffener positioning

The first step towards interpreting a layout is to identify stiffener position. This is typically done by visualizing high density elements to isolate primary members. They appear at the beginning of the optimization as it can be observed in Figure 2.16 showing the density contour of layout I at different iterations. They can be considered as supporting the global deformation of the structure. The density result also defines members with lower density which can be considered as secondary stiffeners as they appear later in the iterations. They contribute to minimizing total compliance by supporting the bay formed by the primary stiffeners. They also provide support to primary stiffeners as the design space is fully attached together. Both high and low density members can be interpreted as potential beams by the designer.

Although they are part of the topology result, keeping the low-density stiffeners for a direct interpretation can be discussed. Their position is sensitive to optimization parameters which makes it difficult to justify their individual existence. Moreover, many of these are developing from primary members and do not have a significant effect on load path. Finally, the bay dimension resulting from the position of the secondary stiffener may not be realistic as it is based on a linear analysis. In summary, the low density features may be less important to generate the initial design concept, but may be required in a subsequent step to deal with bay support. The following discussion on beam interpretation will thus focus on the primary stiffening suggested by the topology layout.

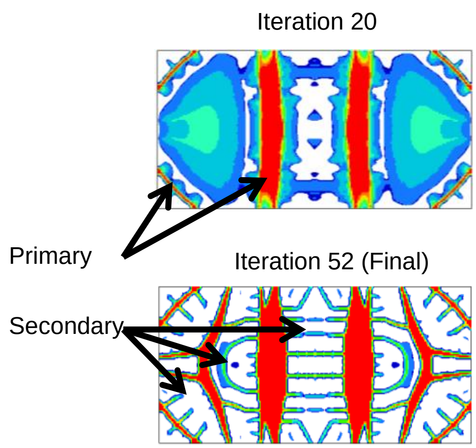


Figure 2.16 : Stiffener positioning interpretation

2.7.2 Stiffener interpretation

Once the position of a stiffener has been determined, the last needs to be interpreted into a beam to generate a design concept. Unfortunately, it cannot be done directly since the dimension and the cross section of the beams modelled by the topology design space are not realistic. This can be illustrated by interpreting the large center beams formed in layout I as shown in Figure 2.17. The function of this beam is obvious as it supports the bending of the plate. However, the dimension of the beam modelled by the high density elements is not realistic for a design concept, as it is not related to sizing constraints such as stress or displacement. Moreover, the full rectangular cross section modelled by the high density shell elements is not appropriate since an I cross-section is much more efficient in bending for a same section area. Therefore, the large beam in the center portion of layout I is interpreted into an I beam where the dimensions of the section are determined in a subsequent sizing step to respect the stress and displacement constraints. This illustrates how the cross-section and dimensions of the beam displayed on the density contour plot need to be interpreted by fully understanding the functionality of the beam in the topology layout.

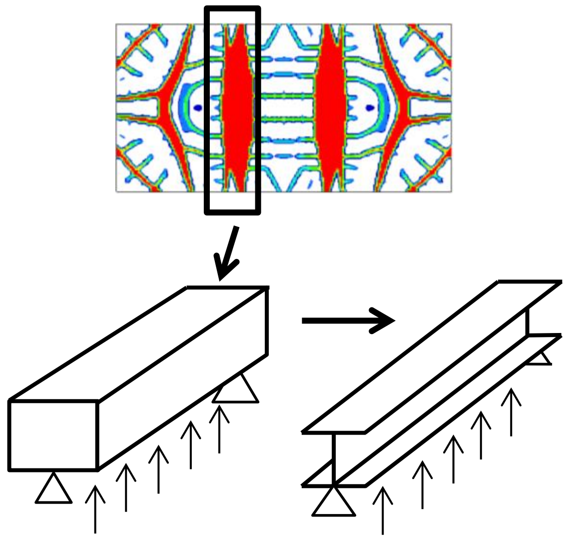


Figure 2.17 : Interpretation of a stiffener

2.7.3 Stiffener connectivity

The interpretation becomes more complicated when several beams are connected together. This connectivity introduces various types of loading in beams such as local transverse shear, bending and torsion. This phenomenon is illustrated in Figure 2.18 where both beam 1 and 2 have the function of supporting the plate. Individually, they both sustain bending load due to the pressurized plate as presented in the last example. However, since they are connected, shear, bending and torsion can be transferred at their junction.

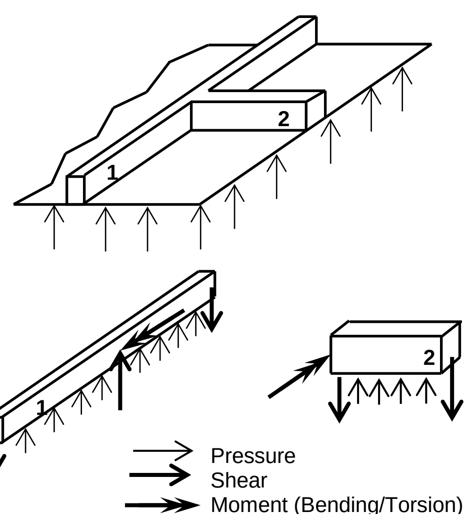
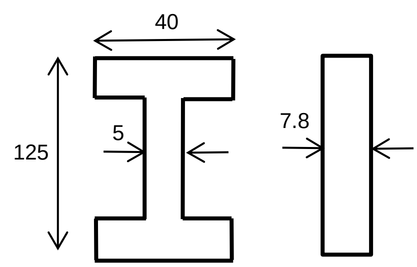


Figure 2.18 : Load transfer at connection

This load transfer at the beam intersection makes the selection of cross section complex. The last is typically selected based on its efficiency for certain types of loads. Figure 2.19 presents an example comparing the bending moment of inertia (I) and the torsional constant (J) of an I and a rectangular section with the same section area (A). It shows that inertia of an I beam is higher than a rectangular section but its torsional constant is lower which makes it a better choice for bending than for torsion.



		I section	Rectangle	Ratio I/Rectangle
A	[mm^2]	975	975	1.0
I	[mm^4]	2.0E6	1.3E6	1.5
J	[mm^4]	8.0E3	1.9E4	0.4

Figure 2.19 : Effect of cross section geometry on torsion and bending properties

Choosing a cross section is easy if the functionality of a beam is obvious but it might not be the case as illustrated in Figure 2.20. As shown on the left side of the figure, beam 1 is wide enough for its torsional stiffness (GJ) to exceed the bending stiffness (EI) of beam 2. It can therefore provide a clamping support to beam 2 to limit its deflection. In that case, choosing a section with good torsional stiffness for beam 1 is important to fulfill its support functionality for beam 2. On the other hand, illustration on the right shows that a thinner beam 1 that has a smaller torsional stiffness can be interpreted as a simple support for beam 2. Choosing a section with good torsional capability would not be important here as the main functionality of beam 1 would be to support plate bending. This example illustrates how difficult it can be to understand beam functionality and make an appropriate cross section selection when various connections or intersections are present in the layout.

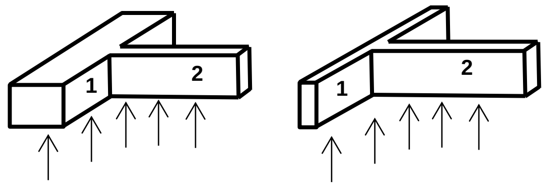


Figure 2.20 : Understanding connected beam's functionality

The challenges associated to the interpretation of high density elements into beams can also be observed using some examples taken from layouts I and II as shown in Figure 2.21. These connections are subject to interpretation since the function and type of load sustained by each beam is not evident.

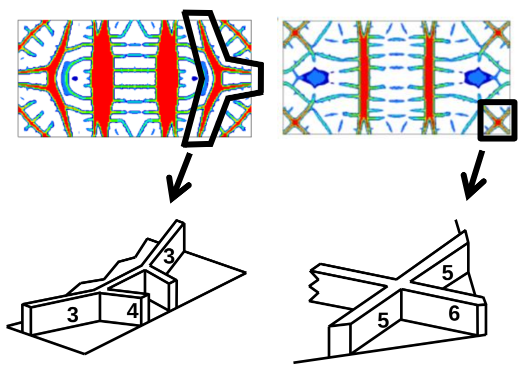


Figure 2.21 : Connection situations

In layout I, the purpose of beam 4 can be interpreted as supporting the curvature of beam 3 therefore limiting its torsion due to transverse pressure load. Once again, this connection generates a combination of bending, shear and torsion in the central portion of beam 3.

In layout II, the addition of beam 5 creates a clamping support for beam 6 as it is attached to the corner of the plate. This short beam has to sustain a large shear load transferred from beam 6 which requires a thick web. In return, this connection also creates bending and torsion on beam 5.

In summary, the overall interpretation of the beam's connectivity can largely influence the designer's choices when developing the design concept such as the type of cross section, type of connection, initial dimensions, etc.

2.7.4 Sources of interpretation complexity

The generation of layouts that are complex to interpret are unlikely to be avoided. All the elements of the design space are connected together and this is why the layouts obtained can be hyperstatic. In other words, the stiffeners interact together and the solution is not unique. A slight modification on a stiffener will affect the others which makes the interpretation and sizing difficult as many local optimums exist.

Moreover, the full rectangular cross section modelled by the design space has a good shear, torsional and bending capacity that generates layout with complex beam loading. It makes the use of other efficient cross section challenging which affects the final performance of the design. Unfortunately, it is not possible to modify the optimisation problem in order to privilege simpler loading. For example, it would be interesting to isolate the torsional component of the compliance shell elements' compliance. This could control the type of load in the beams formed in the layout.

Finally, it is interesting to note that topology optimization of shell structures with in-plane loading do not have this complex bending and torsional coupling in the members formed (Figure 2.22). In that case, topology optimization has the tendency to create truss structures where members are mainly loaded axially by tension or compression. This axial load eliminates the need of choosing an efficient cross section as its stiffness is only proportional to its cross area. Therefore, it is easier to make a direct interpretation of a topology layout for in-plane structures compared to out-of plane plate structures.

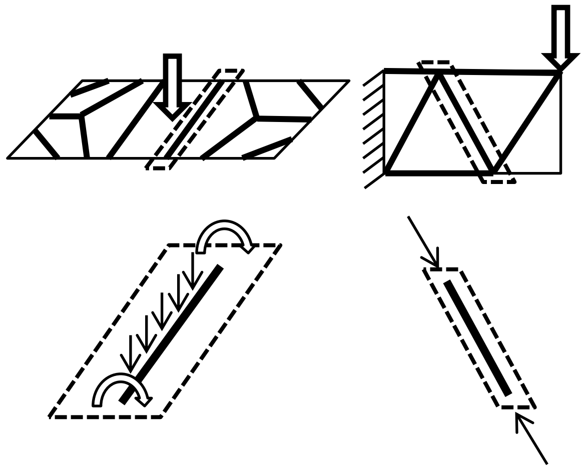


Figure 2.22 : In-plane vs out-of-plane topology optimization

2.7.5 Interpretation of selected layout

The challenges associated to layout interpretation grow with the number of connections (nodes) between stiffeners and the sizing becomes complex as many local optimums exist when choosing beam sections and dimensions. Moreover, a non-conventional concept has a steep learning curve and an important engineering effort is required to become confident with the final design. Finally, the manufacturing of layouts with a high number of nodes is cumbersome as each connection introduces stress concentrations and weight.

Consequently, a layout that has limited number of nodes and where beam functionality can be easily interpreted is selected for the performance estimation in this paper. Layout II (Figure 2.15) has many intermediate density stiffeners and its load paths are not clearly defined. Layout III and IV are similar and show clear stiffening pattern but were generated by modifying the basic topology optimization problem. Lastly, layout I shows a clear primary stiffening pattern that is simple to understand. It is the reason why it is selected to perform the initial interpretation (Figure 2.23).

By examining the proposed configuration one can note that beam D is the result of a contraction to a single beam. This modification is made because in this case, using a single beam instead of two can achieve the same functionality of supporting the angle along beam B to avoid torsion. All beams are then mainly loaded in bending in this layout and using an I cross section is hence justified. The performance estimation of this interpretation and variants of it are presented in the next section.

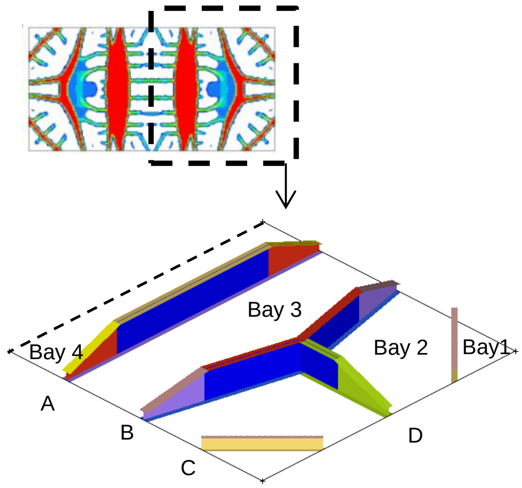


Figure 2.23 : Topology design interpretation

2.8 Performance estimation

This section presents the mass estimation of the topology layout and compares it with the typical design. The assumptions concerning the sizing of beams and skin presented in section 2.4.3 are used. In order to minimize mass, a gradual height reduction (taper) is also allowed where primary stiffeners carry lighter bending load. This taper is defined by gradually reducing stiffener's height to one fourth of its value along a distance of twice the original height, which is a typical practice in the industry.

Three different concepts are presented. The first is directly based on the interpretation presented in the last section where only the primary stiffeners are considered. The second adds secondary stiffening to support the large bay and reduce mass. The last is a global interpretation where primary stiffeners are placed in order to limit bay size thus eliminating the need for secondary stiffeners.

2.8.1 Primary Stiffening

The first mass estimation is performed on the interpretation of the primary stiffeners only (Figure 2.23,Table 2.1). The mass of beam A accounts for half of the total mass of beams. This means that the beam is highly loaded and could be divided into more beams supporting the same load as shown in section 2.8.3. Beam D is lightly loaded and reaches its minimum thickness values. However, its height cannot be reduced as it needs to be connected to beam B in order to support it. Its mass could be reduced by reducing flange width and increasing the taper, but it would have a small impact on total mass and would not change the conclusions of the performance estimation. Finally, the height and flange width of beam C are reduced to minimize its mass as it is lightly loaded.

The mass of skin shows that the large bay (2, 3 and 4) formed by the primary stiffeners have a significant impact on the total mass of the design. In comparison with the typical layout, the total mass of beams is lower (12.8 vs 15.5 kg). However, the larger skin mass (18.8 vs 9.3kg) penalizes the total mass and makes it heavier (31.3 vs 24.8 kg). It illustrates the importance of considering the need for skin support and therefore the bay's dimensions when interpreting a design. It shows that the effect of adding secondary stiffeners should be considered.

Table 2.1 : Primary stiffeners mass

Component	Mass (kg)
Beam A	6.4
Beam B	4.7
Beam C	0.6
Beam D	0.8
Total Beams	12.5
Skin	18.8
Total	**31.3**

2.8.2 Secondary stiffening

The effect of considering secondary stiffeners is evaluated by adding small beams to support the large bays formed by the primary stiffeners.

As discussed in section 2.7.1, it is not necessarily advisable to use the position of secondary stiffener suggested by the topology result. Instead, the secondary stiffeners are positioned in order to use the minimum skin thickness everywhere as it is the case for the typical design (Figure 2.24). These secondary beams are not attached to the primary stiffeners web in order to minimize their impact and avoid new connections. The dimensions of the secondary stiffeners are determined by using the same approach used for the primary stiffeners. However, the flange width is reduced to 20mm as those beams are lightly loaded.

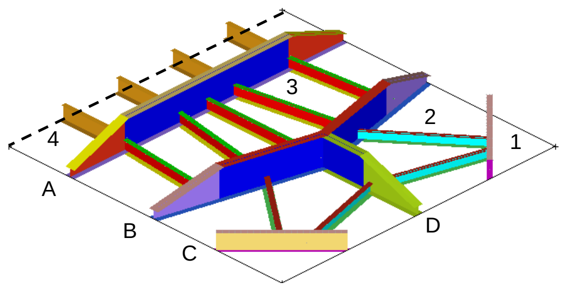


Figure 2.24 : Secondary stiffening placement

The thickness of the webs is set to its minimum value of 1.25mm as the lower heights are not critical for local web buckling. The results obtained are shown in Table 2.2. The addition of secondary stiffeners is drastically reducing skin mass since the minimum thickness is used for all bays. Thus, the mass reduction of the skin is higher than the mass added by the secondary stiffeners. It results in a mass reduction for the entire layout and makes it an efficient design choice.

Table 2.2 : Secondary stiffening mass

Component	**Mass (kg)**
Sec bay 2	1.2
Sec bay 3	1.9
Sec bay 4	1.0
C	0.8
A,B,D	11.9
Total Beams	16.8
Skin	8.7
Total	**25.5**

The estimation suggests that this interpretation results in a similar performance compared to a typical layout (25.5 vs 24.8 kg). However, due to the assumptions used, the uncertainty of the mass estimation prevents us from demonstrating the superiority of a design.

The addition of complexity associated to the topology layout may not add value to the final performance of the design in this particular case study.

2.8.3 Global interpretation

The experience acquired during this extensive topology study can be used along with engineering reasoning to inspire the major load path philosophy and perform a global interpretation.

This is not directly based on a specific topology layout but is directly inspired by the combination of layout I, III and IV. The logic of the proposed layout is to position the primary stiffeners to obtain minimum thickness bays without using secondary stiffeners.

The interpretation is presented in Figure 2.25. As discussed earlier, the mass of beam A is large compared to the other beams and the last can be divided in more beams to share loading and regulate beam dimensions. This is also in accordance with layout III and IV presented in section 2.7 where several beams are formed in the central portion of the plate. Therefore, the proposed layout divide the central portion of the plate by splitting beam A into beam AA and beam AB that are placed in order to have the same pitch as the typical design. Stiffener C is constantly present in layouts suggested by the topology and is kept for this interpretation. However, its length is increased in order to maximize the dimension of bay 1 while using minimum skin thickness. Beam D is split in order to fulfill its support function to beam B while creating smaller division for bay 2. The position of beam D and B is selected to provide uniform bay division that respects displacement criterion at minimum thickness.

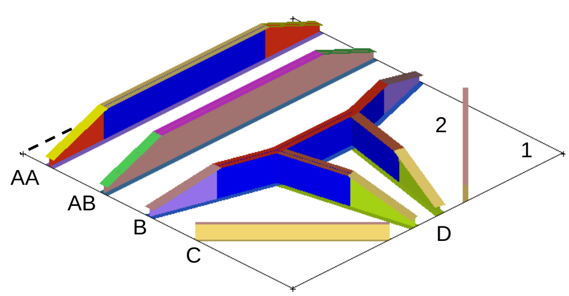


Figure 2.25 : Global interpretation

The results of the sizing are presented in Table 2.3. The replacement of beam A into beam AA and beam AB almost splits mass evenly in each beam. The mass of beam AB is slightly higher as it is surrounded by a larger bay on one side. Their added mass is the same as the original beam A but their smaller pitch eliminates the need for secondary stiffeners. As it was the case for the large bay interpretation, the thickness variables of beam D reach their minimum value but its mass cannot be reduced due to its connection to beam B constraining its height. The mass of beam C increases as it is longer than it was in the large bay design where its position was directly inspired from the density result (1.6 vs 0.64 kg). The total mass of this layout is lower than the two other interpretations and is competing with the typical design (23.4 vs 24.8 kg). The mass of the typical design can however be easily reduced by using the same taper allowed for the interpretation resulting in a mass of (23.4 kg).

Table 2.3 : Global interpretation design mass

Component	**Mass (kg)**
Beams AA	3.1
Beam AB	3.3
Beam B	3.9
Beam C	1.6
Beam Ds	2.0
Total Beams	13.9
Skin	9.4
Total	**23.4**

2.8.4 Results synthesis

A summary of the different mass obtained is presented in Table 2.4. The results show that the minimum mass of the topology interpretation is similar to the performance of a typical design using the same assumptions.

Table 2.4: Summary of mass estimation of layouts

	Mass (kg)		
	Beams	Skin	**Total**
Typical			
No Taper	15.5	9.3	**24.8**
With Taper	14.0	9.3	**23.4**
Topology			
Primary	12.6	18.8	**31.4**
Secondary	16.8	8.7	**25.5**
Global	13.9	9.4	**23.3**

This result cannot be generalized as it is based on a single design case and a set of topologies and interpretations. Topology could perform better than a typical design for a more complex design space where an obvious solution is unlikely. Moreover, the performance estimation is based on several simplificative assumptions and should be further developed in order to be representative of the performance that would be obtained at a detailed design level.

However, this does not affect the conclusion that can be drawn from the present study. The performance improvement of a topology design is significant compared to a uniform thickness plate (23.3 vs 118 kg, 80% Improvement). However, the improvement is drastically reduced when compared to a typical and intuitive design for stiffened pressurized plates (23.3 vs 23.4 kg, <1% Improvement). Moreover, the particularity of the stiffened pressurized plate problem makes the generation, interpretation and sizing of a topology layout challenging. The designer needs to consider bay dimension independently from the topology result in order to achieve better performance. Considering manufacturing constraints and exploring local optimums is mandatory when exploring the design space. Finally, this section showed how important it is to have a global vision of the topology layouts along with engineering judgment when designing based on topology optimization.

2.9 Conclusion

The case study presented on optimal stiffening of a pressurized plate highlights that topology optimization can lead to a design with similar performance compared to a typical design but there is no significant improvement as it is the case when compared to a uniform thickness design. For this simple design case, the challenges associated to generating, interpreting and sizing a topology layout do not justify the use of such design as the engineering and manufacturing cost increases without guaranteeing a performance improvement. However, this conclusion cannot be generalized as topology design process could lead to better design concepts for more complex problem where a typical solution is less obvious. Moreover, it is likely that the layout suggested by the topology design process yields better performance when also considering in-plane loading as it was the case for other industrial case studies. It would be worth exploring in further work by combining in-plane and out of plane loading affecting a real bulkhead.

This study points out how the topology optimization design process includes several challenges when applied to find optimal stiffening of pressurized plates in an industrial context. The out-of plane nature of loading and the local optimums obtained result in layouts that are sensitive to optimization parameters and are complex to interpret. The lesson learned is on the significance of considering many different layouts when interpreting a design as the solution is not unique. Moreover, the designer needs to understand the functionality of the features observed in the layouts to reduce complexity. Using the knowledge acquired from the topology study and combining it to his critical thinking, the engineer can avoid local optimums and perform an interpretation closer to a global optimum. This advice can be generalized to any design case when using density topology optimization method to generate design concepts.

2.10 Acknowledgement

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CHAPTER 3 DESIGN PROCESS COMBINING AXIOMATIC DESIGN AND TOPOLOGY OPTIMIZATION

The typical design process based on topology optimization present several challenges as discussed throughout Chapter 2. The definition of the topology design space, its exploration and its interpretation into a feasible design are always key steps. This information is now used to propose a new design process addressing the second research question: How to address the identified challenges of the actual topology optimization design process?

This chapter presents the developed design process where axiomatic design is combined to topology optimization. It results in an innovative and comprehensive approach to the generation of design concepts. Axiomatic design is an approach that focusses on product functionality that helps understanding the design problem and leads to innovative and efficient solutions. This method is appropriate to address the challenge identified concerning the importance of understanding the functionality of the features suggested by the topology optimization. Moreover, this method provides a systematic approach for design that also allows the integration of another method such as topology optimization into it. It can also be used to perform the reverse engineering of an actual design in order to capture the actual knowledge. Finally, it can support the development of new design concepts starting from a clean sheet by considering customer needs. Other design approaches could have been selected but this research only focused on axiomatic design.

The principles of axiomatic design are first presented to introduce the reader to this design methodology. The new design process combining axiomatic design and topology optimization is then presented. A simple application of the process is also performed to illustrate its potential advantages and help its understanding. Finally, the process is also applied to the pressurized plate example presented in Chapter 2.

3.1 Definition of axiomatic design

3.1.1 Introduction to axiomatic design

The design of complex product is a challenge faced everyday by engineers and designers. Experience, knowledge and intuition are often the main tools used to generate design concepts.

This approach is not reliable and can lead to costly iterations especially for innovative designs. There is no systematic methodology to explore the design space and propose different concepts in order to compare them and select the most efficient. Axiomatic design is a design methodology developed by Professor Nam P. Suh at Massachusetts Institute of Technology that can be used to support the design process (Suh 2001). This approach proposes a framework where the design problem is decomposed into functional requirements (FR) associated to design parameters (DP). This decomposition is made by respecting two simple axioms: the independence and the information axiom.

The independence axiom states that the independence of the functional requirements has to be accomplished. This ensures a controllable design and avoids unintended consequences. The information axiom states that the information content of a design should be minimized. This means that a simple design will be more robust and its chances of success will be maximized. This framework provides a scientific basis for design and avoids subjectivity. It is a tool that allows productive discussion and reduces the iterations required to obtain a final design. Some basic principles of axiomatic design need to be defined in order to use it. These are presented in the following discussion. The reader is referred to Brown’s text (Brown 2014) and Suh’s book (Suh 2001) for more information.

3.1.2 Domains

Axiomatic design framework uses a structure that is called domains. These domains contain different elements concerning the design problem and are required to apply the axiomatic principles. The domains and their relations are presented in Figure 3.1.

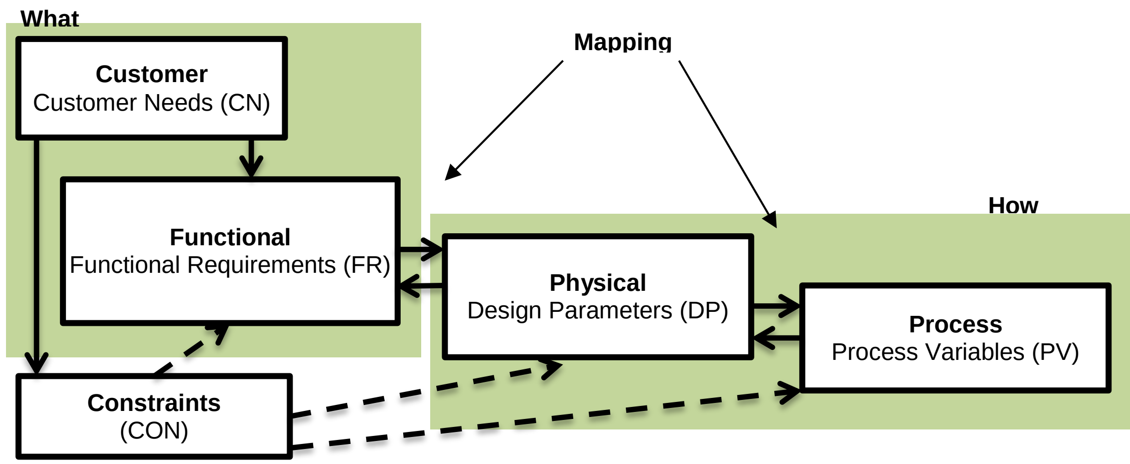


Figure 3.1 : Axiomatic design domains and their relations[6]

The Customer domain contains all the customer needs (CN) as it summarizes all the information provided by the customer. The information is translated into elements that are called customer needs. These customer needs cannot be directly used to create a design concept and it needs to be translated in the constraint and the functional domain.

The functional domain contains the information concerning what the design should do. The elements of this domain are called functional requirements (FR). The functional requirements are statements that start with a verb and they need to be defined without thinking about the solution. The combination of the CN and the FR address **what** the design should do.

The physical domain contains the design parameters (DP) that explain how to fulfill the FRs. These are expression starting with a noun as they represent a physical solution. It addresses **how** the design fulfills its purpose.

[6] Adapted from Brown (2014)

The process domain represents how the DPs will be obtained. It contains elements called Process Variables (PV) that represent how the DP will be manufactured or assembled for example. However, in most cases, the search for solution using the axiomatic approach focuses on the functional and the physical domain.

The Constraint domain contains all the constraint (CON) that applies to the design. These constraints affect the design decisions in all other domains. Input constraints can be imposed by the customer need and affect the whole design such as cost and mass for example. System constraints appear during the selection of design parameters. The constraints can sometimes be mixed with FRs and it is good to remember that FRs are always associated to a single DP.

The **mapping** between the FRs, DPs and PVs is a decomposition process that implies certain reciprocity between domains as presented next.

3.1.3 Axiomatic decomposition process

The core of axiomatic design method is to develop the FRs and the DPs based on the CN input. These need to respect the two axioms in order to obtain a good final design. This mapping is done by using an approach called zig-zagging. This name represents the constant switching between the functional and the physical domain as illustrated in Figure 3.2.

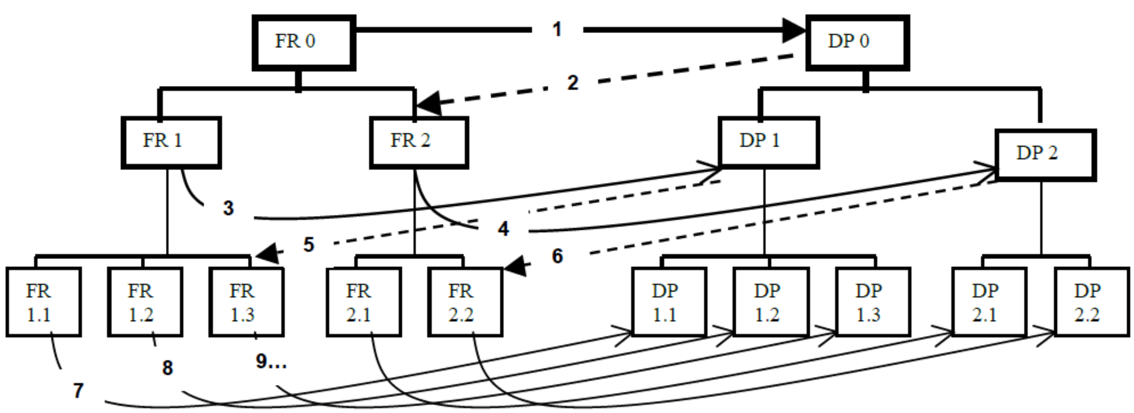


Figure 3.2 : FR-DP decomposition process and Zig-Zagging[7]

[7] Reproduction from Brown (2014)

The first step is to define the top level FR (FR0) based on the CN. A first "zig" is then performed and its associated DP (DP0) is obtained (1). The "zag" is then used in order to define the first level FRs (2). These FRs needs to be independent between each other and together need to represent the parent as a whole. This principle is called collectively exhaustive and mutually exclusive (CEME) by Professor Brown and it assures the respect of the independence axiom. A good approach to respect this principle is to use a decomposition theme such as load or energy transfer for example. The designer can ask himself: What are the functionalities of DP0? He can then use a decomposition theme to develop the sub FRs. For example, the sub FRs of the design of a car (DP) based on the motion theme could be to provide forward and backward motion (FR1) and to provide ability to turn (FR2). It is important to remember that the definition of the FRs needs to be done without considering the potential physical solution of the same level. Once the sub FRs have been defined, the corresponding DP can be defined using the “zig” again. For the car example, the solution to first level FRs could be to have engine powered wheels (DP1) and a directional wheels (DP2). Each FRs must have its unique DP but this does not prevent the physical integration of the DP as will be discussed later. The respect of the two axioms is checked at each level of the decomposition with the design matrix as discussed next. The zig-zagging can be continued until the design becomes obvious.

This FR-DP decomposition is not a straightforward process as it creates discussion and requires much iteration. This step is the core of axiomatic design power as it ensures that the focus is made on fulfilling the functional requirements with an efficient and minimal physical solution that respects the two axioms.

3.1.4 Design matrix and independence axiom

The relations between FRs and DPs can be visualized into what is called a design matrix. The matrix represents the relation between the FRs and the DPs. The matrix is always square because the number of FRs and DPs must be the same. It allows visualising if the independence of the FRs is respected. Figure 3.3 presents the three different types of matrix that can be obtained. The relation between a FR and a DP is represented by an X. The decoupled matrix represents a design where each DP only influences one FR. It is the best design possible because it is easy to adjust each DP in order to fulfill each FR. This type of design can rarely be obtained and thus a decoupled matrix is also acceptable according to the independence axiom. This lower triangular matrix represents a design where each FR can be fulfilled by adjusting the DPs in a specific order. A coupled matrix is bad design according to the independence axiom because this will require several iterations in order to find a combination of DPs that will fulfill the FRs. It is therefore necessary to modify the FRs and the DPs to obtain a decoupled or uncoupled matrix.

The design matrix is a powerful tool to visualize the interactions between the FRs and DPs. It allows the designer to be conscious of the impact of the modification of a DP on the FRs. It is also useful to check the design matrix while doing the decomposition in order to ensure that no undesirable coupling occurs.

	DP1	DP2	DP3
FR1	X		
FR2		X	
FR3			X

Uncoupled

	DP1	DP2	DP3
FR1	X		
FR2	X	X	
FR3	X	X	X

Decoupled

	DP1	DP2	DP3
FR1		X	X
FR2	X	X	
FR3		X	X

Coupled

Figure 3.3 : Type of design matrix in axiomatic design

3.1.5 Information axiom

The information axiom is not affecting the decomposition as much as the independence axiom. It can be used to select between different potential solutions to the same FR. The simpler is the selected solution (contains less information), the higher are its chances to succeed. This can be quantified mathematically by the probability of respecting an FR. Meanwhile this exercise is not performed in this thesis.

3.1.6 Physical integration

As discussed earlier, the functional independence of the FRs and DPs must be kept independent in order to obtain an uncoupled or a decoupled matrix. However, this does not mean that a physical independence must be kept. It is possible to combine DPs into one physical component as long as their functionalities are not coupled. Also, incorporating several design parameters in a single component can help respect the information axiom by reducing the complexity of the design. For example, the design of a tool to allow eating liquid food (FR1) and solid food (FR2) can be solved by using a spoon (DP1) and a fork (DP2). It is possible to imagine a tool where both of these solutions are physically integrated at both end of a utensil without affecting functionality. However, the designer needs to be careful with physical integration as it can sometime bring coupling between DPs that were not present in the original design matrix.

3.2 Overview of the new design process

The design process developed combines axiomatic design and topology optimization. The main idea of the design process is to use topology optimization as a tool in the axiomatic decomposition of the structural design. Therefore, the axiomatic design principles are at the center of the design process in each step. The process developed is divided in two phases: The concept generation phase as well as in the sizing and analysis phase (Figure 3.4).

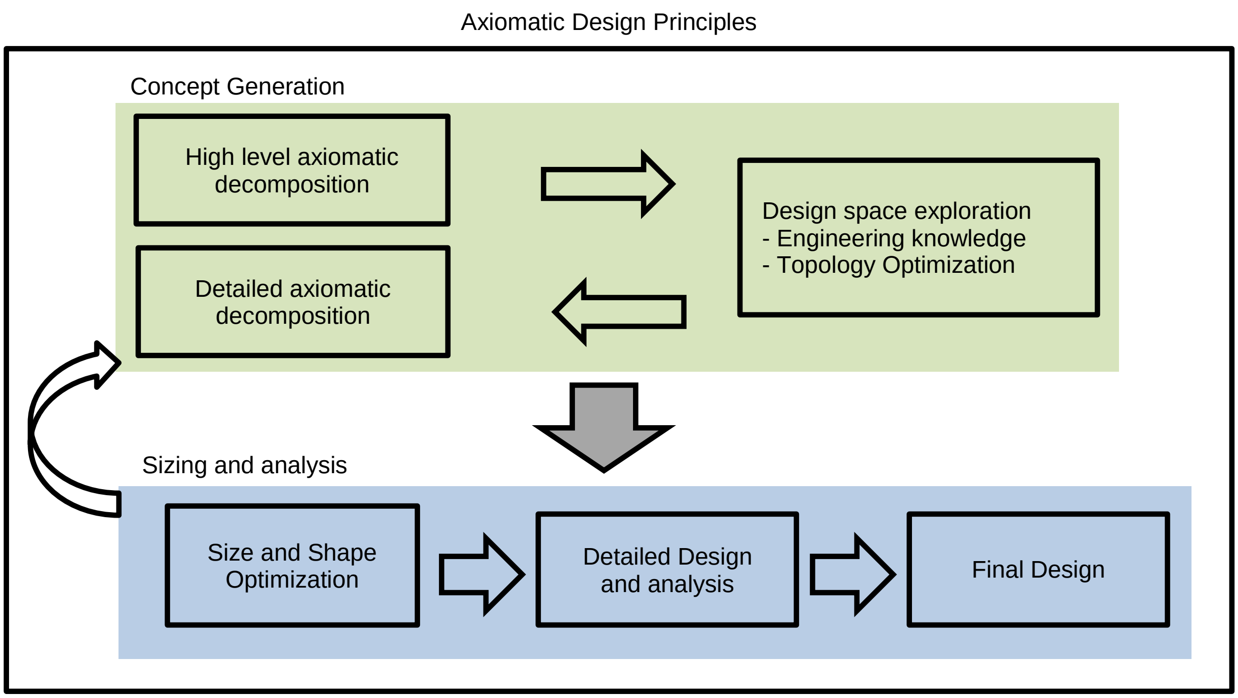


Figure 3.4 : Conceptual visualization of the Design Process

This thesis focus on the **concept generation phase** as it is where the novelty of the process is. A high level axiomatic decomposition of the design problem is first performed to capture customer needs and transfer it into the functional and the physical domain and obtain a clear definition of the design problem. Topology optimization is then used as a tool along with engineering knowledge to explore the design space and acquire information to develop the axiomatic decomposition further and obtain a feasible design concept that fulfills the functional requirements while respecting constraints.

The **sizing and analysis phase** is following the concept generation. It is required to converge towards a final feasible design that respects all constraints. This phase is not developed in detail in this thesis since it is performed in any design process. However, it is important to remember that each step is also supported by axiomatic design principles in the process suggested. Therefore, FR-DP decomposition can be used at a detailed level if necessary. This means that the axioms and domains are always present to affect design decisions. The decoupling of the functional requirements of component is favored and the designs that maximize the chance of success are selected.

Finally, figure 3.4 illustrates a **feedback loop** between the sizing and the concept generation phase. This loop is illustrated since new information concerning the design can be learned and it may sometimes be necessary to go back to the concept generation phase to account for it. A good axiomatic decomposition along with a good design space exploration should reduce the risk of feedback loop as the design concept results from a systematic approach where most of the constraints and requirements are captured. Moreover, the axiomatic decomposition and the design matrix help identifying the potential impact of changes. Finally, the decoupling of the functions of the design concept minimizes the impacts of such design modifications.

3.3 Design concept generation process

3.3.1 Overview of the concept generation process

The novelty of the process lies in the concept generation phase (Figure 3.5). In this phase, the customer needs are first translated in top level constraints, FRs and DPs to clearly define the design problem. Topology optimization is then used to explore the design space and visualize potential load path. In other words, it gives insight of what the design solution (DPs) could look like. A functional interpretation of the topology results is performed after in order to develop sub-FRs of the design problem. This step ensures that the designer understands and defines the functionality of the structural feature suggested by topology optimization before jumping to the physical interpretation of the results. It is the core of the design process as it forces to step back from the topology result and it avoids potential pitfalls associated to direct interpretation. Finally, the physical interpretation transforms FRs into DPs that define a design concept that respects axiomatic design principles while being inspired from topology optimization.

Note that the figure presents feedback loops. These loop account for cases where new information learned at a lower level requires going back to previous steps to explore the design space further or redefine axiomatic decomposition. This should not be performed systematically and is only displayed to illustrate that this type of feedback can occur.

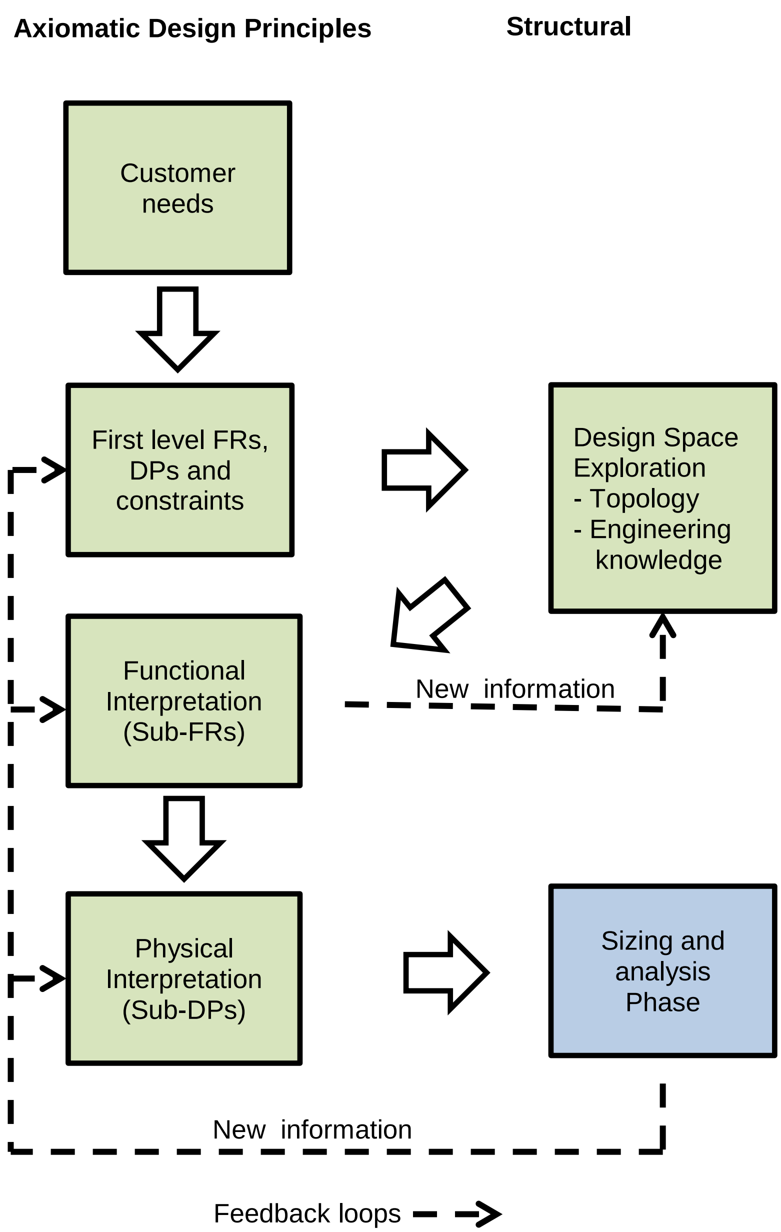
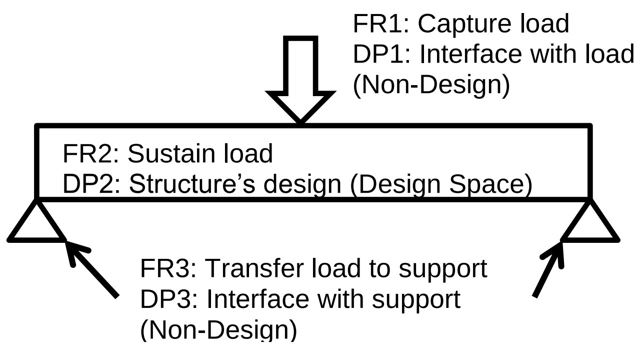


Figure 3.5 : Overview of concept generation phase

3.3.2 First level FRs, DPs and constraints

The main functionality of a load bearing structure is to transfer load from one point (or zone) to another. This functionality is directly compatible with the load transfer theme. As mentioned earlier, decomposition themes helps obtaining independence of FRs and a certain coherence of the mapping. Other themes could also be explored such as energy transfer for example but it is not performed in this thesis. This theme is naturally linked with topology optimization problem as it shows optimal material placement to transfer load. It is therefore easy to link structural functionality (FRs) to a topology model (DPs). The resulting general first level FR-DP decomposition is presented in Figure 3.6.



FR0	Transfer load from one point to another	DP0	Load bearing structure
FR1	Capture Load	DP1	Interface with load (Non-Design)
FR2	Sustain load	DP2	Structure’s Design (Design Space)
FR3	Transfer Load to support	DP3	Interface with support (Non-Design)

Figure 3.6: General first level FR-DP decomposition of structures based on load transfer theme

A general top level DP (DP0) is defined using the "zig" from FR0. DP0 can then be decomposed into first level FRs by using the "zag" technique. Using the load path decomposition theme, the functionalities of the structure (DP0) are to capture (FR1), sustain (FR2) and transfer (FR3) load. This set of first level FRs is collectively exhaustive and mutually exclusive with respect to their parent (FR0). The first level DPs are obtained by once again using the zig technique. The first levels FRs are therefore respectively associated to DPs concerning the interface of the structure with load (DP1), the structural design itself (DP2) and the interface with the structure’s supports (DP3). Note that the design space is located in DP2 and that DP1 and DP3 represents non-design space as the interface with load and boundary condition is fixed.

Other inputs from the customer need such as strength or manufacturing requirements are recorded in the constraint domain (CON) as they are not related to the main functionality of the structure. They can therefore affect the design at any step of the process.

This first level decomposition captures the main functionality of any structural component. It is used to clearly define the design problem while keeping design freedom to its maximum in a solution-free environment. The core of the structural design is embedded into FR2 and DP2 which is where the load is sustained. The idea is to get as much information possible on the potential efficient load path in order to develop FR2 further. Therefore, the design space can be explored by using engineer's knowledge and experience along with topology optimization.

3.3.3 Topology design space exploration

Topology optimization is used to explore the design space. It is not suitable to consider a single topology optimization result as observed in Chapter 2. Therefore, this exploration step requires an exploration of the sensitivity of the topology result. The last can be related to many different sources as shown in Table 3.1.

Table 3.1: Potential source of load path sensitivity

Source	**Examples**
Optimization parameters	Objective and constraints, Manufacturing constraints, variation range, other
Boundary conditions	Discrete vs uniform, location, relative stiffness, other
Loading	Relative magnitude, Location, Combined load case influence, other
Design Space	2D vs 3D, dimensions, discretization (mesh size and element type), other

It is not necessary to perform an extensive evaluation of potential effects but it is strongly suggested to get confident with the topology result and its origin. This avoids having the narrow vision of a local optimum, specific to the density method, and increases the chances of understanding functionality of generated features.

The exploration step also suggests looking at the **evolution** of the topology during the iterations. It provides great insights on the sources and functionality of the members generated. For example, topology optimization has the tendency to create members connecting stress concentration points which is observable in the history of iterations. This adds to the knowledge acquired when exploring the design space.

3.3.4 Functional and physical interpretation

The functional interpretation step is used to synthetize the results obtained in the topology exploration phase and define sub FRs associated to it. The main idea is to consider all topology results and identify common features and load path. Engineering judgment must then be used to analyze and understand functionality of the redundant features observed. As mentioned earlier, it allows having a global vision of the topology intent and avoiding potential pitfalls associated to direct interpretation of a topology. This knowledge is finally used to develop sub FRs (FR2.X) and define functionality concerning how the design should sustain load (FR2).

The physical interpretation step consists of finding DP2.Xs associated to the FR2.Xs developed. These DPs are then physically integrated together to form a design concept. It is important to note that the design concept is subject the constraints domain which helps generating a feasible interpretation and avoid unnecessary iterations. The design matrix can then be analyzed to evaluate potential coupling in the design.

3.3.5 Summary of the concept generation process

This section described each steps of the concept generation process. These are summarized by Figure 3.7.

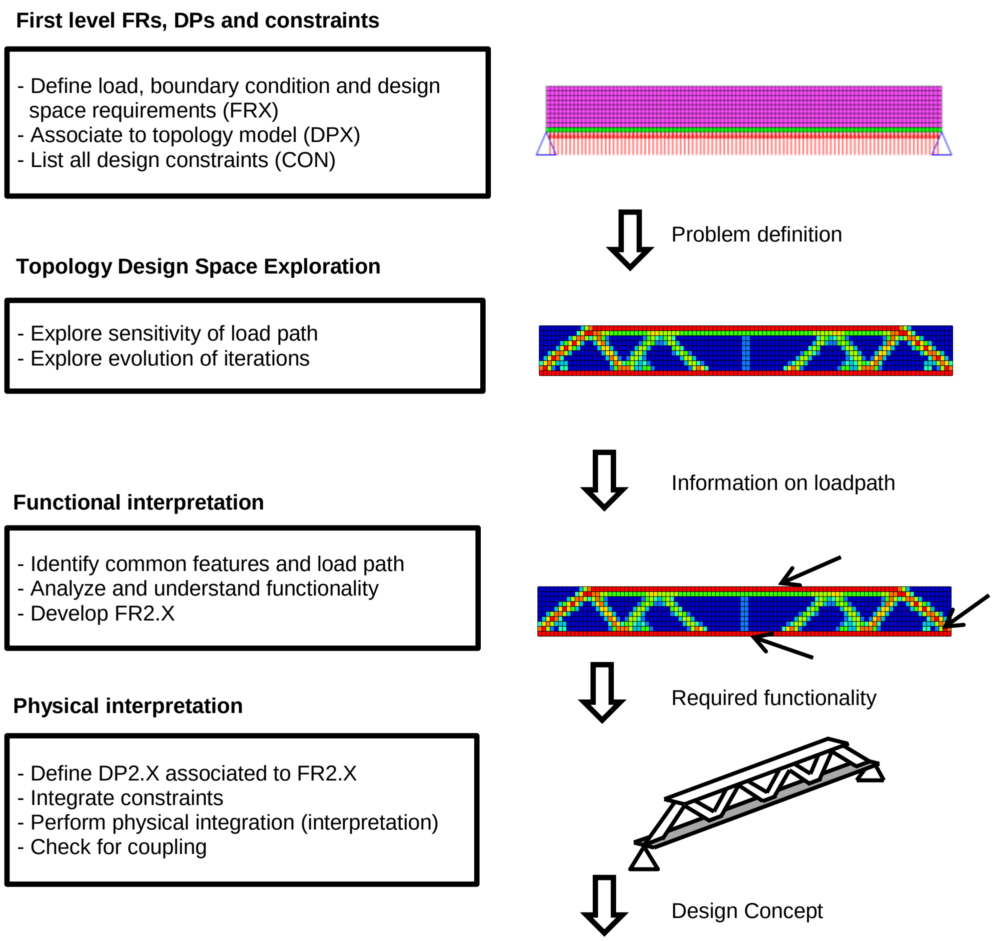


Figure 3.7 : Summary of the concept generation process

3.4 Simple application of the concept generation process

The design process combining axiomatic design principles with topology optimization is applied to a simple beam design example in order to illustrate its capabilities. The customer needs a beam that will transfer a uniformly distributed load to its supports (simple support). The beam has to be manufactured by typical assembly or machining methods and its mass has to be minimized under stress and displacement constraints. Finally, the width and height of the beam cannot be higher than one tenth of its length.

3.4.1 First level FRs, DPs and constraints

The first step of the process is to transform the customer needs into first level FRs, DPs and constraints. The constraints, the first level FR-DP decomposition and the corresponding topology design space are shown in Figure 3.8. The FRs are defined according to the load transfer theme as proposed in the design process. The FRs and CON 3 are used to define the topology design space in order to obtain information concerning FR2. The first FR defines the non-design space and the load applied to the model. The second FR along with CON3 determines the design space dimensions. The third FR defines the boundary conditions of the model.

FR1	Capture uniformly distributed load	DP1	Non-Design Space/Loading
FR2	Sustain load	DP2	Design Space
FR3	Transfer load to simple support	DP3	Support/Boundary conditions

CON1	Minimize mass
CON2	Manufacturable
CON3	Design space dimensions
CON4	Maximum Stress
CON5	Maximum Displacement

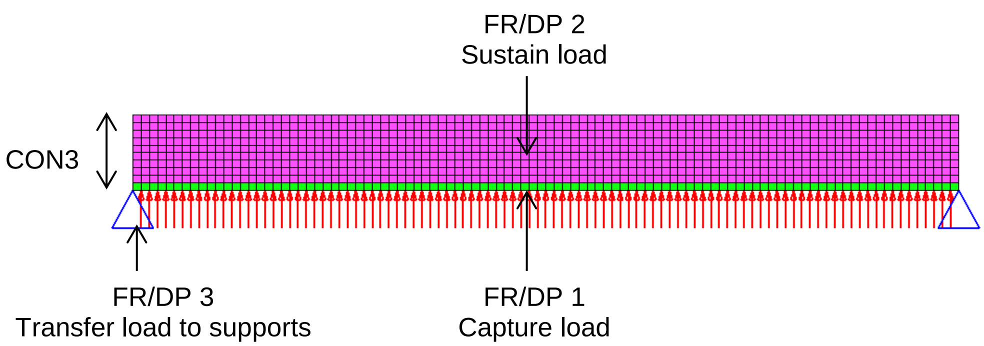


Figure 3.8 : First level FRs, DPs and constraints of beam

3.4.2 Topology design space exploration

Topology optimization is now used to explore the design space. The compliance is minimized for a constrained volume fraction in order to visualize optimal material placement and load path. The topology result is not sensitive to mesh size, volume fraction and manufacturing constraints. It is sensitive to loading (FR1) and boundary conditions (FR3) but it is not presented since the example is clearly defined.

The design space is explored with a 2D design space made of shell elements with topology and free-size (continuous variable thickness) optimization. A 3D design space is also explored with topology optimization. Figure 3.9 shows that similar results are obtained for all approaches. The material is concentrated in the top and lower portion of the design space and a truss is formed in between. The free-size result is not forming a truss as it is not forced to form discrete members. The 3D result with no extrusion constraints is also not forming a truss structure between the top and lower part of the design space.

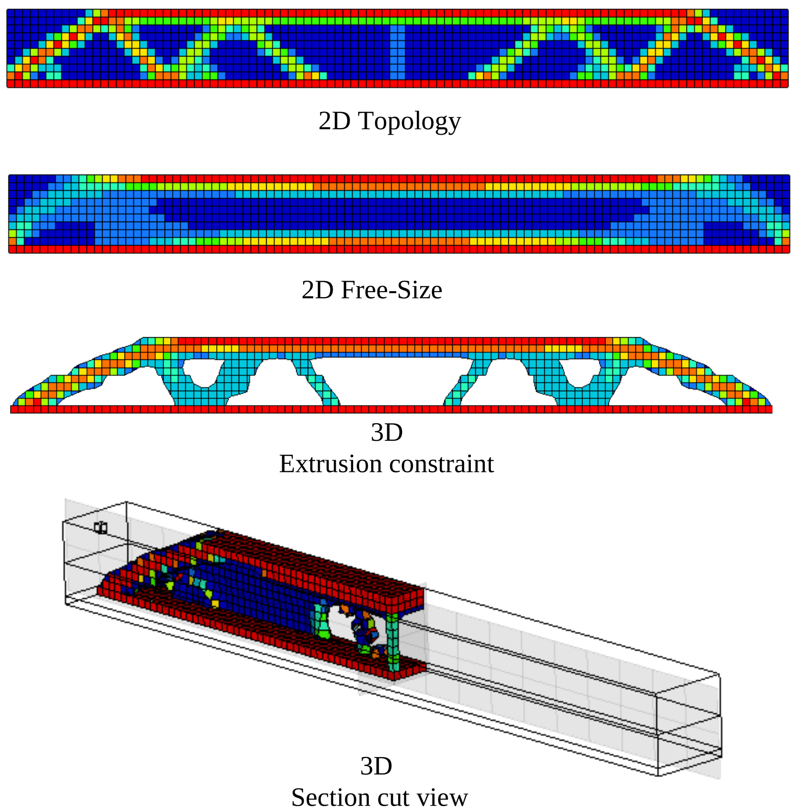


Figure 3.9 : Topology design space exploration of beam

3.4.3 Functional interpretation

The design space exploration by topology optimisation provides great insights of the functional requirements of a design solution. The result could be directly used to create an interpreted model and optimize it as it is done usually. However, the design process developed forces the designer to perform another step in order to understand the functionality of the features suggested by the topology result before jumping to the interpretation. This step ensures a deeper understanding of the features retained and the proper definition of the required independent functions. It also reduces the risk of performing an inefficient interpretation.

This simple example allows using beam theory to understand the intent of the topology result. The shear and bending moment diagram of the beam are presented in Figure 3.10 along with the 2D topology result.

Material is constantly concentrated in the top and lower portion of the design space in zone 2 and 3 where bending moment is important. This maximizes the beam bending inertia since material placed far from the section centroid impacts inertia proportionally to the square of the distance due to the parallel axis theorem. This theorem is valid as long as the top and lower portions are connected together and working as an entity.

This connectivity is ensured by the truss or the web observed in zone 1 and 2 where there is high transverse shear load. The functionality of this topology feature is to capture transverse shear and transfer it into the top and lower portion of the design space in order to maintain structural integrity. The feature observed is directly linked to the magnitude of the transverse shear as it is gradually vanishing towards zone 3 where no shear is present.

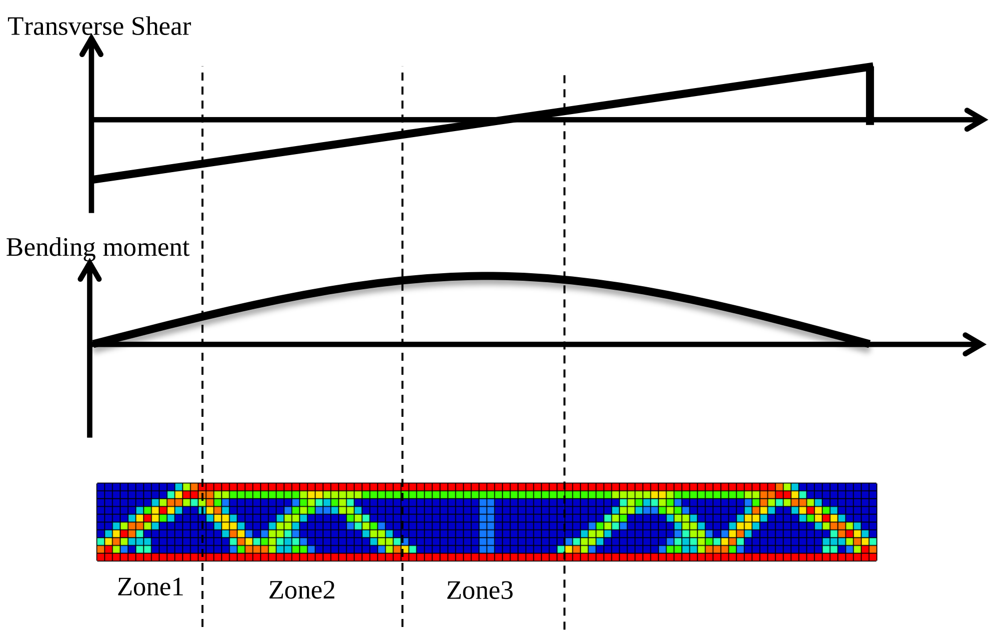


Figure 3.10 : Beam shear and bending diagram

Now that the functionality of the features observed in the topology layout is understood, it is possible to define the sub levels of FR 2 (Figure 3.11). The definition of these sub-Frs may seem obvious for this example but doing this exercise is primordial to ensure that the interpretation (selection of DPs) will focus on fulfilling the FRs.

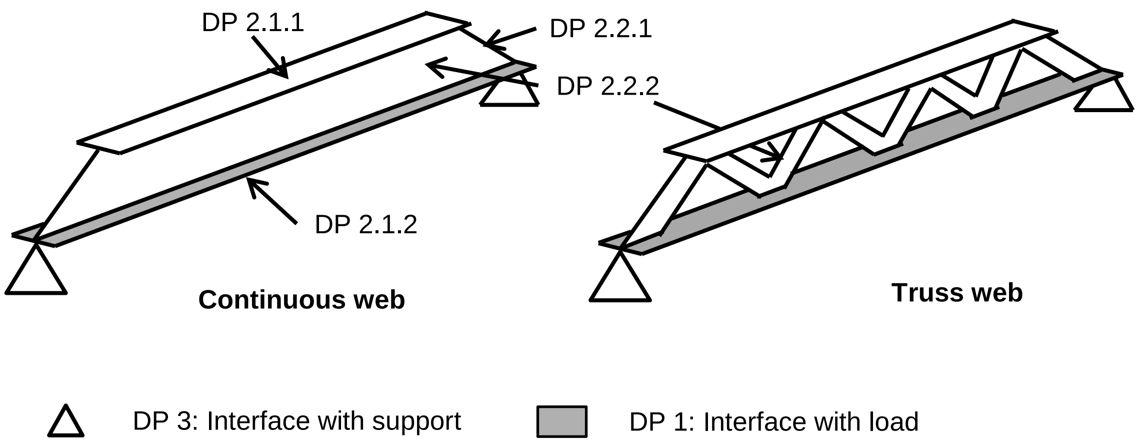
FR2	Sustain load
FR2.1	Sustain bending
FR2.2	Sustain transverse shear (maintain structural integrity)

Figure 3.11 : Development of FR2.X

3.4.4 Physical interpretation

The DPs associated to the FRs developed are presented along with a visualisation of the design solution in Figure 3.12. The creation of beam flanges (DP2.1) to support bending (FR2.1) is suggested by the topology solution. The use of a web formed by a truss (DP2.2) is suggested by the topology result to sustain the transverse shear load and maintain structural integrity (FR2.2). The free-size and 3D result also propose using a continuous web (DP2.2) to fulfill the same function. Although this definition of DP might sound redundant and obvious, the designer now has a sound and simple interpretation of the topology result based on functionality of the features. This allows detaching the interpreted design from the topology result and continuing to the next step while respecting its philosophy.

The principles of axiomatic design can then be used to develop the interpretation further by developing the subs FRs. For example, the function of the flanges is to support compressive and tensile load to balance the bending moment applied to them. Therefore, the FR-DP decomposition can illustrate that need so that the designer is aware that a stable bottom flange should be used to avoid its local buckling (DP2.1.2). The same thing can be done for the web or the truss design where the need for sustaining shear varies along beam span.



FR2.1	Sustain bending	DP2.1	Material placed to maximise inertia (top and bottom flanges)
FR 2.1.1	Sustain tensile load	DP2.1.1	Top flange cross section area
FR 2.1.2	Sustain compressive load	DP 2.1.2	Stable bottom flange cross-section area
FR2.2	Sustain transverse shear to maintain structural integrity	DP2.2	Web/Truss
FR 2.2.1	Sustain high shear with no bending in zone 1	DP2.2.1	Web/truss taper
FR 2.2.2	Sustain variable shear in zone 2 and 3	DP2.2.2	Variable web/truss in zone 2 and 3

Figure 3.12 : Physical Interpretation

The constraints such as manufacturing and mass minimisation (CON 1 and 2) also need to be considered at each step of the FR-DP decomposition. For example, the mass impact of using a uniform thickness web is captured along the interpretation process. These constraints can also affect the choice of a web or a truss design. Aspects such as assembly, commonality of parts and cost can be captured and can influence such important design decisions. Moreover, other constraints such as the ones concerning stress and displacement (CON 4 and 5) can be used during the sizing optimisation.

The axiomatic approach also imposes checking the design for coupling between FRs and DPs at each step of the decomposition. This ensures that the interpreted design minimizes coupling and avoids complex issues associated to it. Finally, the respect of the second axiom also supports the interpretation to maximize the chances of success.

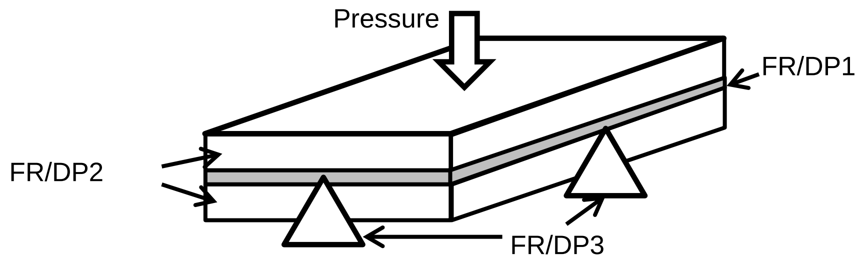
In summary, this simple example illustrates how topology optimization can be used as a tool in the axiomatic design framework. It also shows how this design process suggested provides good basis to support the definition and the interpretation of a topology optimization towards a sound and feasible design.

3.5 Application to pressurized plate example

The design process developed is applied on the pressurized plate example presented in Chapter 2. The example showed several challenges associated to the design of stiffened pressurized plate by topology optimization. This section illustrates how the design process developed supports the concept generation phase and helps overcoming difficulties associated to topology generation and interpretation. The design problem consists of finding the stiffener layout on a pressurized plate that will minimize mass while respecting stress and displacement constraints.

3.5.1 First level FRs, DPs and constraints

The customer needs are first transformed into FRs, constraints and DPs in order to support the development of the topology optimization problem according to the load transfer theme (Figure 3.13). The need to capture the pressure load (FR1) requires a minimum skin thickness value (DP1) that represents a non-design space. The load transfer requirement (FR3) defines the boundary condition of the model (DP3). Finally the design space (DP2) represents the potential solution to the load sustaining requirement (FR2).



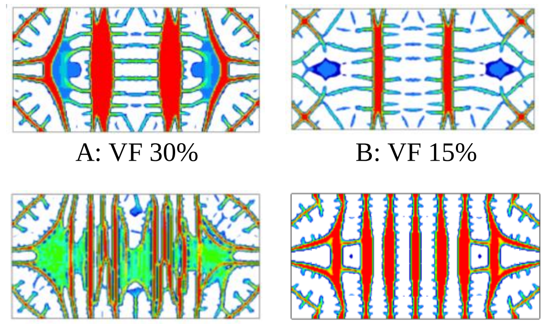
FR1	Capture pressure load	DP1	Minimum skin thickness (Non-Design Space)
FR2	Sustain load	DP2	Stiffener configuration (Design space)
FR3	Transfer load to simple support	DP3	Support/Boundary conditions

CON1	Minimize mass
CON2	Manufacturable
CON3	Maximum Dimensions
CON 4	Maximum Stress
CON 5	Maximum Displacement

Figure 3.13 : First level FRs, DPs and constraints of pressurized plate problem

3.5.2 Topology design space exploration

Topology optimization is used to explore the design space and provide information to develop FR2. This exploration was performed in Chapter 2 by minimising compliance for a constrained volume fraction (VF). The stress and displacement constraints (CON 4 and 5) were not used as they do not result in discrete stiffening pattern as discussed in the same chapter. The topology result is sensitive to parameters such as volume fraction and manufacturing constraints. The result is also affected when modifying the boundary conditions (DP3) of the model. Figure 3.14 summarizes the result of the topology exploration where different layouts are obtained for the different parameters and boundary conditions evaluated.



A: VF 30% B: VF 15%

C: Maxdim D: Local Support

Note : Density above 10% displayed

Figure 3.14 : Topology design space exploration

The central portion of the plate is stiffened by straight stiffeners along the shortest dimension of the plate. The corner of the plate is stiffened by a stiffener at 45 degrees. The portion between the corner and the center of the plate is stiffened in different ways for the different optimization parameters.

3.5.3 Functional Interpretation

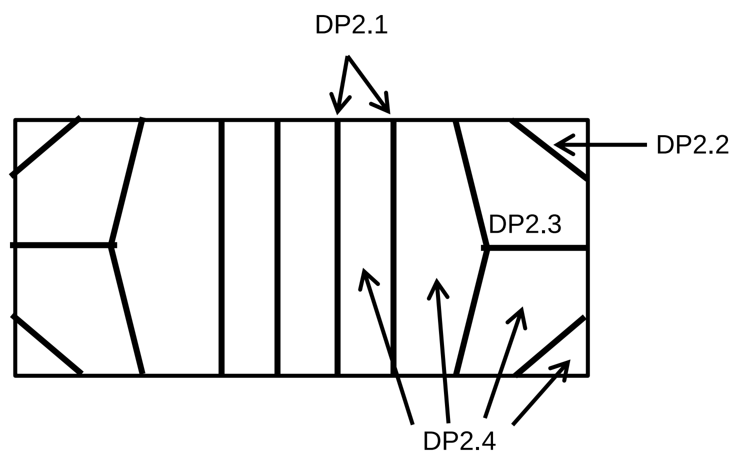
The topology design space exploration is now used to develop FR2 further. Here, engineering knowledge is used to interpret the functionality of the features observed. The topology optimization suggests different forms of stiffening for the different zones of the plate and functional requirements are developed this way. The functionality of the features observed in the layouts is presented in Figure 3.15. The central region needs to be stiffened to avoid its large deformation (FR2.1). The corner of the plate is naturally stiffer because of its geometry and therefore requires different stiffening (FR2.2). The plate also needs to be supported between the corner and the center portion and a transition is required between the two (FR2.3). Finally, the bays generated by the stiffeners need to be supported adequately which calls another function of the layout (FR2.4).

FR2	Sustain load
FR2.1	Support global plate deformation in center portion
FR2.2	Support global plate deformation in corner portion
FR2.3	Support global plate deformation between corner and center
FR2.4	Support local skin deformation

Figure 3.15 : Development of FR2 based on topology results

3.5.4 Physical interpretation

The FRs obtained from the topology results are now used to develop the associated DPs that lead to an interpretation and a design concept. Figure 3.16 shows the FR-DP decomposition of the load sustaining functionality (FR2). As suggested by the topology results, the center portion of the plate (FR2.1) is stiffened by beams parallel to the shortest dimension of the plate (DP2.1). The corner portion is stiffened by a beam attaching both side of the plate at an angle of 45 degrees as suggested by the topology result (DP2.2). The portion between is stiffened by a combination of beams (DP2.3) that create a transition between the center and corner portion of the plate. The last requirement concerning skin support (FR2.4) is associated to the dimensions of the bay created by the stiffeners (DP2.4).



FR2.1	Support global plate deformation in center portion	DP2.1	Regularly spaced beam in center portion of plate
FR2.2	Support global plate deformation in corner portion	DP2.2	Beam at 45 degrees in corner
FR2.3	Support global plate deformation between corner and center	DP2.3	Beams between center and corner
FR2.4	Support local skin deformation	DP2.4	Bay dimensions

Figure 3.16 : Physical Interpretation of stiffened pressurized plate

Once again, the interpretation of the topology results into FRs and then into DPs may seem redundant and comparable to a direct interpretation of the topology result. However, it is important to remember that the design is now detached from the topology result as it is supported by axiomatic design principles. These principles ensure that the interpretation will fulfill the functionality defined while respecting constraints, maximising chances of success and limiting coupling.

The design concept obtained has several beams that can interact with each other and the design matrix is a tool to unravel all these potential interactions and avoid complex coupling in the design (Figure 3.17). The bay dimension is determined by the position of the stiffeners and consequently the skin support functionality (FR2.4) is coupled with all DPs. This coupling influences directly the selection of stiffener position since they have to achieve two functionalities at the same time (global and local deformation support). This will therefore affect the pitch of the central stiffeners (DP2.1), the position of the corner stiffener (DP2.2) and the design of the transition between the central and the corner portion (DP2.3).The designer can create a better interpretation by being aware of this interaction. He can select beam position that will allow using the minimum manufacturable skin thickness (CON2) in order to minimize the total mass of the design (CON1). This essential information is not captured by the topology optimization but is accounted for in the process developed.

	DP2.1	DP2.2	DP2.3	DP2.4
FR2.1	x			
FR2.2		x		
FR2.3			x	
FR2.4	x	x	x	x

Figure 3.17 : Design matrix of concept for the stiffened pressurized plate

The design matrix also shows that there is no coupling between the other FRs and DPs (2.1 to 2.3). This decoupling is directly due to the definition of the FRs and their associated DPs that ensures independent functionality. This means that the design respects the independence axiom and that it will be easy to analyse and optimize. This check is important to perform as it would highlight coupling present in complex layouts suggested by topology optimization. It therefore provides a tool to evaluate the complexity associated to a layout interpretation.

In summary, the design space was explored by topology optimization to visualize potential load path. Different local stiffening needs are identified and are used as a basis to define three different regions: the center, the transition and the corners. A design concept is obtained by placing beams at these locations to fulfill their individual functionality and coupling is then studied and limited using the design matrix. This design process therefore allows a systematic approach to explore design space and develop efficient design concepts.

This application of the design process shows that axiomatic design can successfully support the design by topology optimization and ensures that a sound and feasible interpretation is performed even in the presence of multiple challenges associated to the methodology. Moreover, the process developed does not exclude conventional designs since topology optimization is only used as a tool to explore the design space. Conventional designs are also potential solutions and their contribution to the development of other FR-DP decomposition also needs to be considered. This ensures that existing solution to simple problem will be used even if topology optimization does not necessarily propose it.

CHAPTER 4 CONCEPT GENERATION OF A PRESSURE BULKHEAD

The concept generation process developed and presented in Figure 3.5 and Figure 3.7 is now applied to the flat bulkhead design case. The chapter is organized in sections corresponding to each steps of the process. The customer needs are first presented along with the first level axiomatic decomposition. Topology optimization is then used to explore the design space. After, the functional interpretation step analyses the origin and functionality of the main features observed. The functionalities are finally fulfilled in the physical interpretation step where three different concepts are presented. A discussion concerning the effect of surrounding structure and the local boundary conditions associated to it (FR/DP3) is also presented along with a comparison with a real pressure bulkhead design.

4.1 Customer needs

Figure 4.1 summarizes the customer needs for the rear pressure bulkhead design case. This structure needs to seal the aft fuselage and it must sustain the pressure differential between the cabin and the atmosphere.

The volume required for the installation of systems in the aft fuselage limits the available design space for the bulkhead's structure. Moreover, the space allocation for pressure bulkhead's structure is also often affected by cables and pipes. The location of stiffeners can therefore be constrained by the system installation which creates some non-design space in the optimization set-up.

The bulkhead considered is attached to the fuselage skin and to cabin floor. The longitudinal beams of the floor are therefore contributing to the support of the bulkhead's deformation. This design decision is the result of a trade-off between the reduction of bulkhead weight and the reinforcement of floor necessary to support the load transferred by this attachment. The connection reduces the free bending length of the bulkhead and therefore reduces the required structural mass to support the deformation. However, this attachment introduces tensile load in the floor beams which requires more material to fulfill static and fatigue requirements. The loading on the floor also introduce vertical in plane loading to the bulkhead but it is negligible compared to the pressure load.

The simplified pressure bulkhead studied in this section is inspired from the flat rear pressure bulkhead of a business aircraft from Bombardier Aerospace. It has a radius of 2500mm and the maximum stiffener height allowed is 125mm (5% of diameter) as it was the case for the pressurized rectangular plate. It is connected to the floor that has 9 longitudinal beams and it is also attached to the fuselage formed by a continuous assembly of skin panels and stingers. A detailed description of the dimensions and the finite element model used is given in Appendix A.

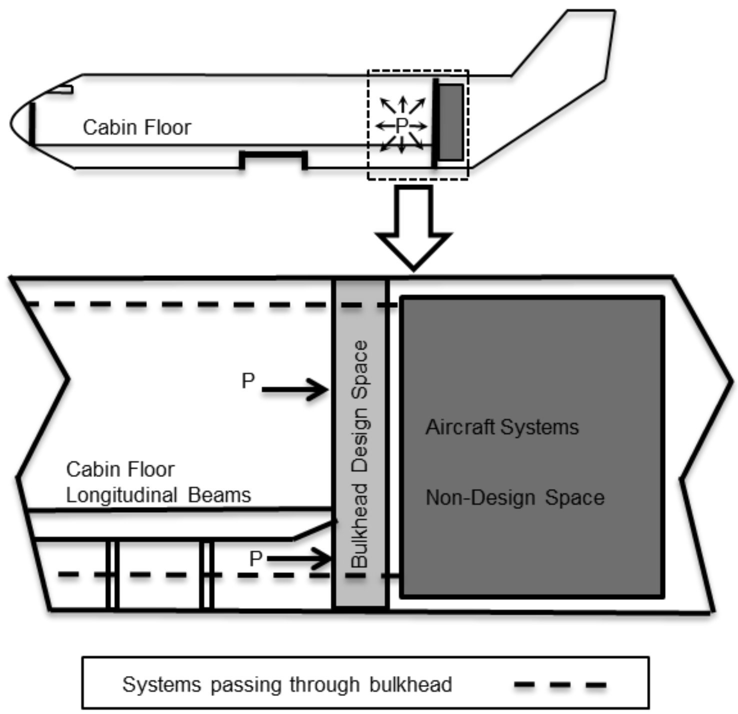
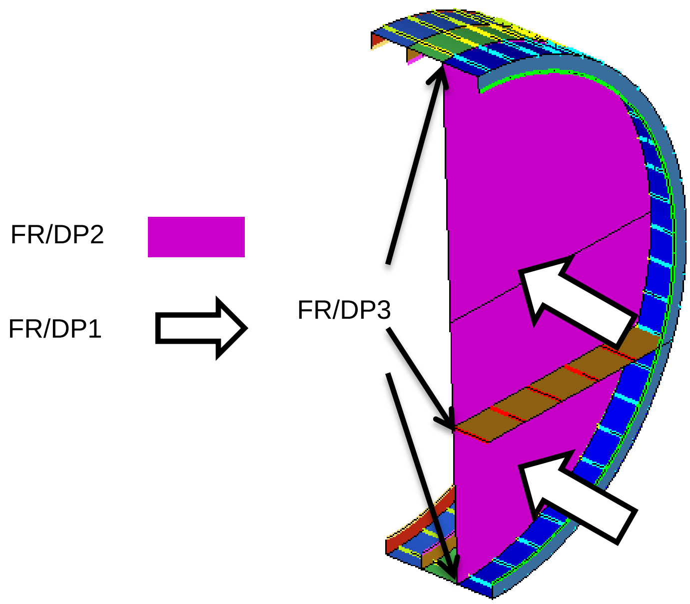


Figure 4.1: Aircraft flat rear pressure bulkhead design space visualization

4.2 First level FRs, DPs and constraints

Figure 4.2 shows the first level axiomatic decomposition and constraints based on the load transfer theme. At this point, it is assumed that the constraint for the allowable design space (CON1) already pushed the design towards a flat pressure bulkhead as mentioned earlier. The pressure load has to be captured (FR1) by a skin (DP1) (of minimum thickness) in order to be transferred as it was the case for the flat pressurized plate example. The load captured by skin has to be sustained and carried (FR2) by the stiffener configuration (DP2) towards the supports. The bulkhead finally has to integrate with the boundary (FR3) using a proper interface (DP3).

Constraints influencing the whole design such as mass, stress and manufacturing are recorded in the constraints domain. As mentioned earlier, the loading transferred from the floor to the bulkhead structure is not part of the functional requirements as it is small compared to the pressure loading. However, it could be integrated into FR/DP1easily if it was to be considered.



FR1	Capture Pressure load	DP1	Skin (Non-Design Space)
FR2	Sustain and carry load	DP2	Stiffener configuration (Design Space)
FR3	Transfer to boundary	DP3	Interface with boundary

CON1	Maximum Design Space
CON2	Allow system penetration
CON3	Minimize mass
CON4	Manufacturability
CON5	Minimize cost
CON6	Minimum Strength, Static, Fatigue, Damage tolerance

Figure 4.2 : First level FRs, DPs and constraints of bulkhead

4.3 Topology design space exploration

The design space (DP2) is explored using topology optimization. The compliance is minimized for a constrained volume fraction as it was the case for the pressurized plate example studied in Chapter 2. The study also highlighted the local optimality of the result and stressed the need to explore the design space with different topology optimisations. This section presents the effect of optimisation parameter to evaluate the sensitivity of the layout. An analysis of iteration evolution is then performed to better understand the source of the features observed. Finally, the influence of discrete boundary condition on the layouts is explored. This exploration phase allows identifying common features between layouts which will be used in the functional interpretation step.

4.3.1 Optimization parameters

The sensitivity of the layout to optimization parameters is studied to ensure a proper exploration of the design space (DP2). The effect of manufacturing constraints and volume fraction are presented since they were identified as having the most impact on the layout on the simplified pressurized plate presented in Chapter 2.

The *mesh size* is first explored along with *manufacturing constraints* such as minimum (MINDIM) and maximum member size control (MAXDIM). The minimum allowable value of MINDIM (2x average mesh size) and MAXDIM (2x MINDIM) are used to evaluate the effect of constraining stiffener width to be smaller than its height (125mm) which is typical for beams. Mesh of 5, 10 and 20 mm are explored to allow using a MAXDIM constraint of 20, 40 and 80mm respectively. Figure 4.3 shows the layouts obtained for the different mesh and manufacturing constraints.

The layout below floor is not affected by mesh size and manufacturing constraint and is therefore a potential candidate of redundant feature for the functional interpretation step. However, the layout is sensitive in the upper portion of the section above floor as the position and number of stiffener is not constant. Mesh size below 20mm captures the local stiffness of each stringer in the top portion of the fuselage which creates a transition zone between floor and top fuselage. This zone does not appear for mesh of 20mm which result in more discrete stiffeners.

There is no significant difference in the layout when using penalization, MINDIM and MAXDIM constraint which means that penalizing thin and large stiffeners does not affect the layout in that case. This may be due to the discrete floor beams that forces stiffeners to pass through them. The mesh of 20mm with penalization gives a slightly different layout in the top portion.

This study shows that the mesh size selected can influence the topology result as it can or cannot capture the effect of boundary conditions. It also showed that the features observed below floor are redundant. The minimum member size constraint is used along with a mesh of 20mm for the next topology explorations as it gives a discrete stiffening pattern and it has a reasonable run time.

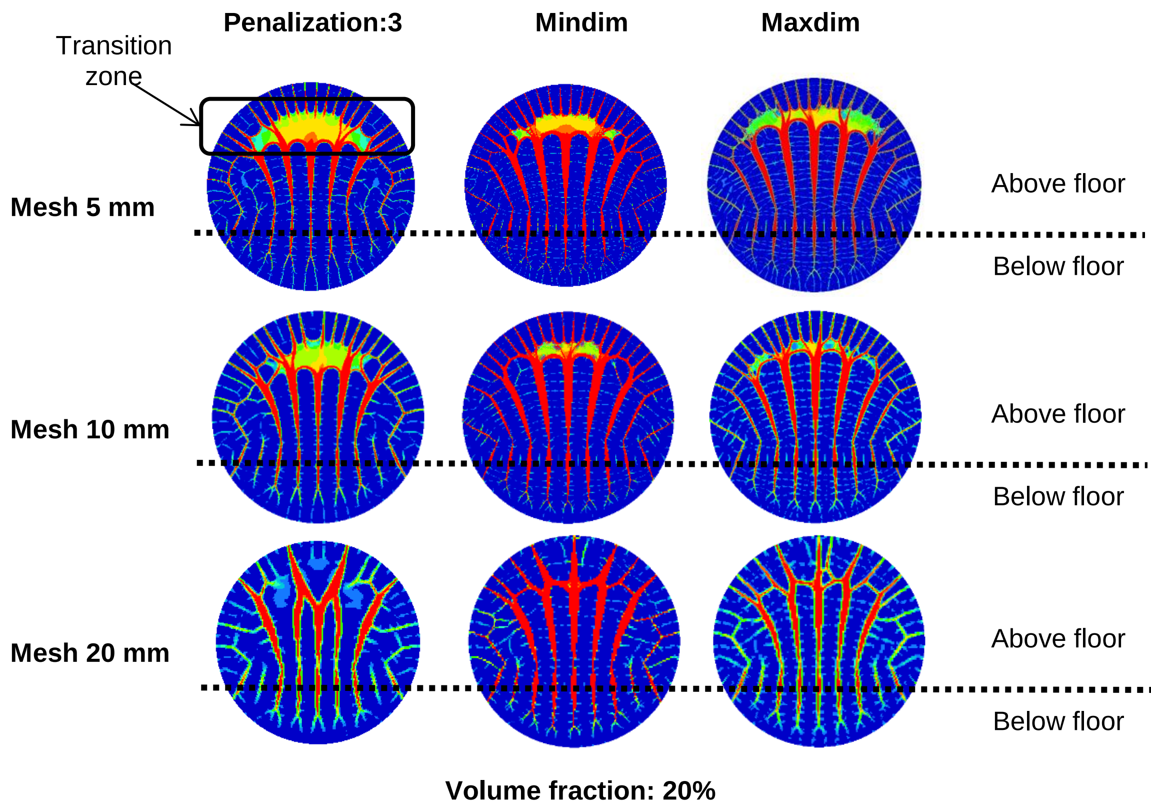


Figure 4.3 : Effect of mesh size and member size control on topology

The effect of *volume fraction* (VF) is studied for values between 5 and 30% (Figure 4.4). The number of stiffeners appearing in the top portion changes for values below 20%. Once again, it shows that the stiffener layout is sensitive above floor but redundant below floor.

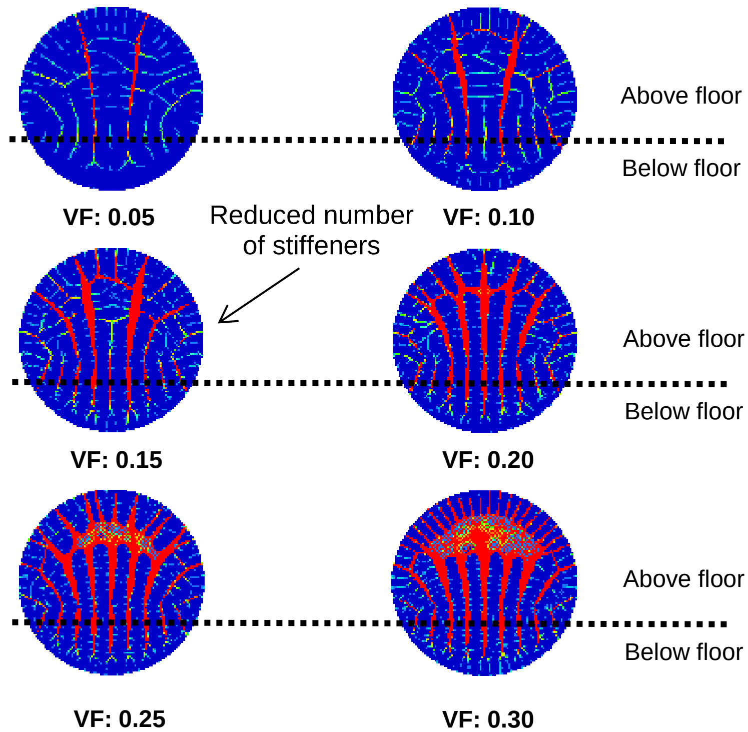


Figure 4.4 : Effect of volume fraction on bulkhead

Other parameters such as symmetry constraint or minimum thickness are not presented since they do not affect significantly the layouts obtained.

The parameter study showed that topology is sensitive above floor where the number, orientation and configuration of stiffeners can vary. The stiffening below floor is relatively constant. The presence of floor is obviously having a major impact on the layout.

4.3.2 Analysis of iteration evolution

The *evolution* of the topology iterations provides useful information about how the load path is developed and how local boundary conditions (FR3) can affect the final layout. The evolution of topology with iterations can be visualized in Figure 4.5 for a volume fraction of 20% with minimum member size constraint and a mesh size of 20mm.

The figure shows that the formation of stiffeners is performed in two steps. The first one consist of forming vertical stiffeners symmetrically from floor beam location as these stiff supports create a stress concentration that has the most significant impact on the compliance objective. Once these stiffeners are formed, the upper portion is forming stiffeners in the shortest direction between the vertical stiffeners and the fuselage.

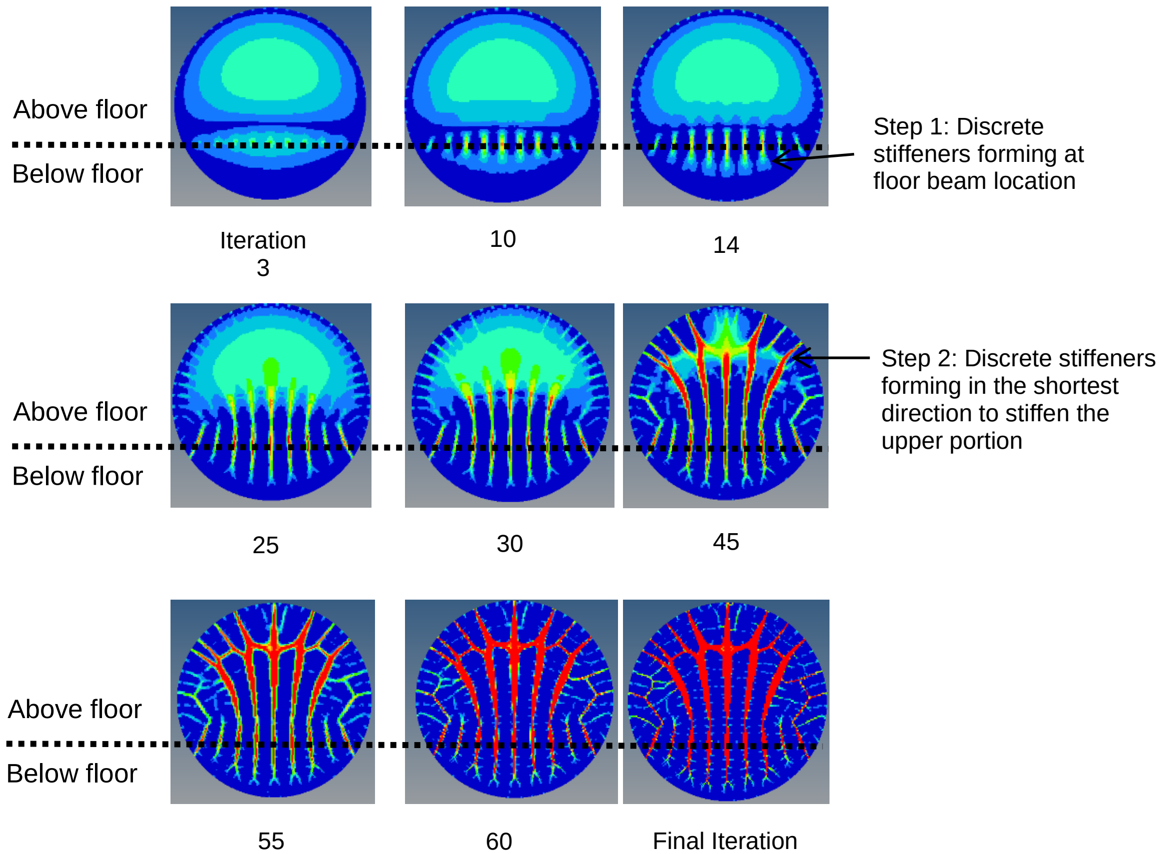


Figure 4.5 : Evolution of iterations

4.3.3 Effect of boundary conditions

The evolution of iterations showed that the stress concentration at floor beam location has a significant impact on the generation of the layout. It affects the initial iterations of the optimization and forces a specific local optimum. Other local optimums can be obtained by modifying boundary conditions (FR/DP3) which affects the first iterations. The impact of local stiffness such as the one related to stiffener interface with fuselage is explored in Figure 4.6. In order to simulate stiffer support for nine vertical stiffeners positioned at floor beam, the out-of-plane translation of nodes inside the design domain is constrained near their junction with fuselage.

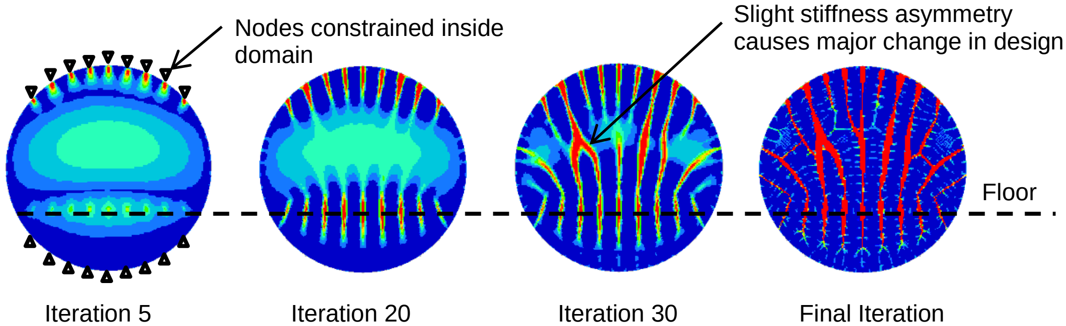


Figure 4.6 : Effect of local support on fuselage at vertical position from floor beam

This local support affects the evolution of the optimization because beams are growing from the top of fuselage and floor beam location. However, beams are still not forming in the bottom portion of the fuselage even if nodes are constrained. Moreover, the small imperfection in the constraints applied to node causes an asymmetric layout which highlights the sensitivity of the topology to boundary conditions.

This study also illustrates how the relative stiffness of beam junction with fuselage influences the final layout. Instead of attaching to each stringer as it was the case on some layouts, the topology attaches the stiffeners to the specified stiffer supports. It is important to keep this in mind since a real stiffener junction will introduce a different local stiffness that will influence the layout. The topology is therefore sensitive to its surrounding and can be significantly affected by simple changes of the boundary condition (FR/DP3).

4.4 Functional interpretation

The results of the topology exploration step are now used to develop sub FRs for the load sustaining and carrying requirement (FR2). The redundant features observed in all topologies during the exploration step are described in Figure 4.7. As observed in the evolution of the topology, stiffeners are forming at floor beam location. In fact, the presence of floor has a major impact on the stiffeners formed. The formation of stiffeners near and below floor is relatively constant. However, the stiffening of the portion above floor is significantly affected by optimization parameters. Moreover, the stiffening above the floor has a discontinuity in its stiffeners as well as an orientation change. The origin and functionality of these particular features needs to be understood before defining functional requirements inspired from topology exploration.

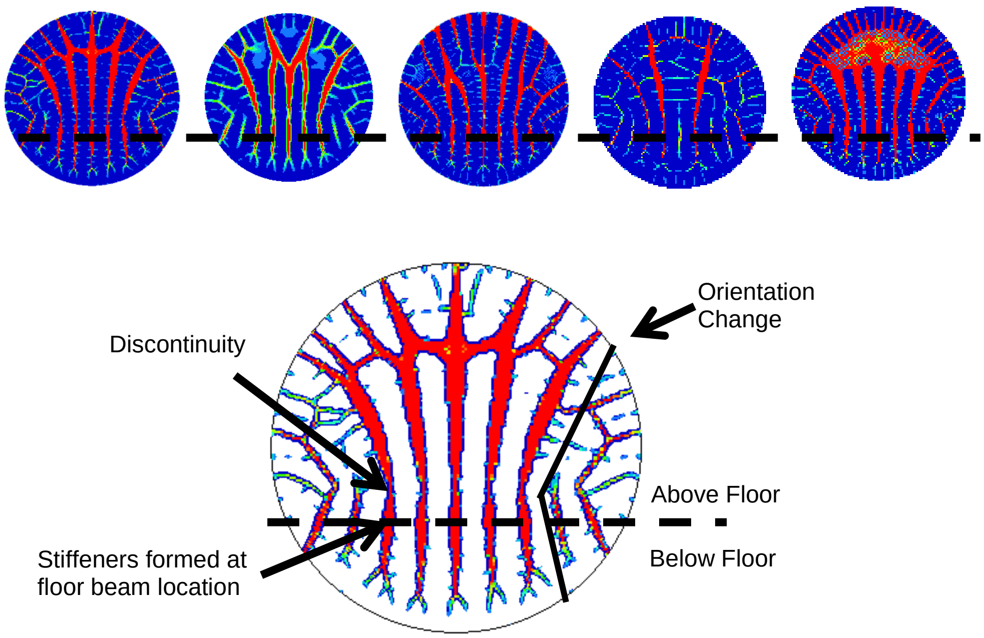


Figure 4.7 : Topology exploration redundant features

4.4.1 On the origin of discontinuity in stiffeners above floor

The discontinuity of the stiffeners above floor can be explained by analyzing the impact of the floor attachment on the design space (Figure 4.8). The figure illustrates how the design space can be visualized as a continuous beam under uniformly distributed load supported at 3 locations (top and bottom fuselage, floor). The support provided by the floor creates a discontinuity in the transverse shear that changes the sign of the bending moment. This change creates a point where there is no moment and therefore a zone with very small strain (deformation) in the design space. The latter is not important for the compliance objective and this explains why the topology is creating a division at its early iterations and creates a discontinuity in stiffeners. The behavior was also reproduced with the topology optimization of a simple beam.

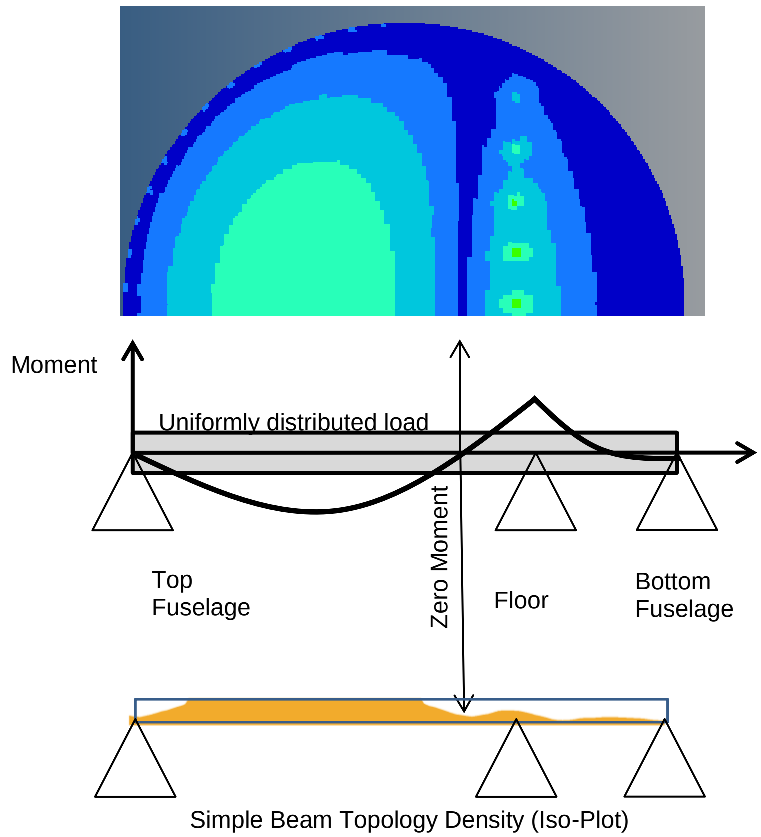


Figure 4.8 : Effect of floor on stiffener discontinuity

Discontinuity and local optimum

It is important to note that this discontinuity is the result of a local optimum. For example, Figure 4.9 illustrates how a continuous beam can be compared to the discontinuous beam suggested by the topology. The advantage of the continuous beam is that the right portion provides a clamping like boundary condition to the left portion which reduces its free length and therefore its deformation. The discontinuous beam suggested by topology is shorter but is simply supported which can result in a larger deformation. Both designs can be used but it is important to keep in mind that the continuous beam will never be suggested by the topology since it always converges towards the discontinuous beam local optimum.

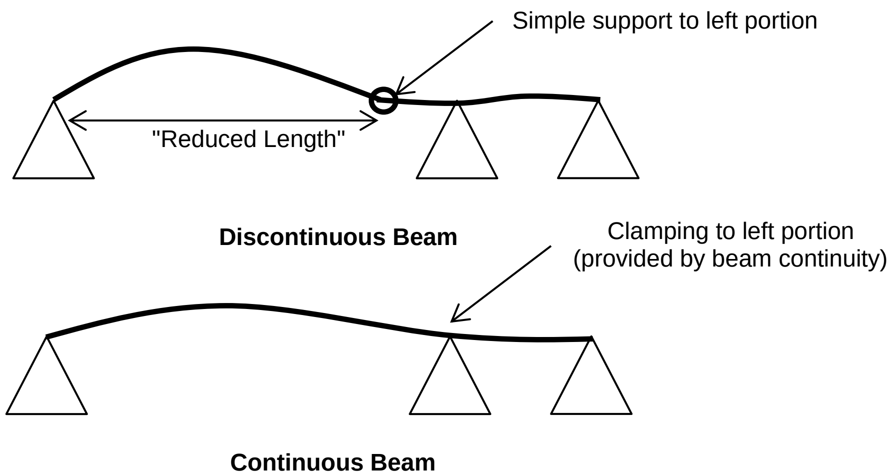


Figure 4.9 : Continuous vs discontinuous beam deformation

4.4.2 On the origin of stiffener orientation change

This discontinuity explains why stiffeners are suddenly changing direction above floor as shown in Figure 4.10. The figure presents a visualisation of an intermediate iteration where upper stiffeners are still not formed. It illustrates how the formation of upper stiffeners can be visualized as a new optimization problem because of the discontinuity. The resulting problem consists of stiffening a simply supported plate which explains why stiffeners are forming to provide a uniform support to the upper portion which explains the orientation change.

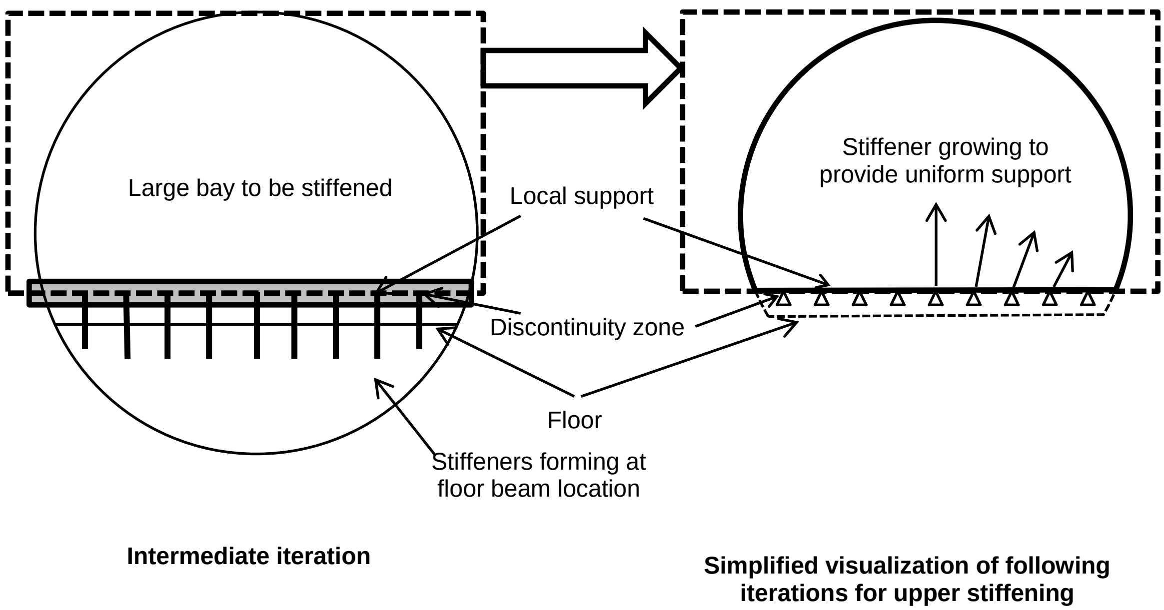


Figure 4.10 : Explanation of stiffener orientation change

Orientation change and continuity

The interpretation of the discontinuity and the orientation change is important as it can have a major impact on the load path. For example, the interpretation of a curved discontinuous stiffener into a continuous one would create significant torsion load on the lower stiffener as bending moment would be transferred (Figure 4.11). This is another important aspect to consider when analysing the topology result since continuous and discontinuous beam do not behave the same way in the presence of curvature.

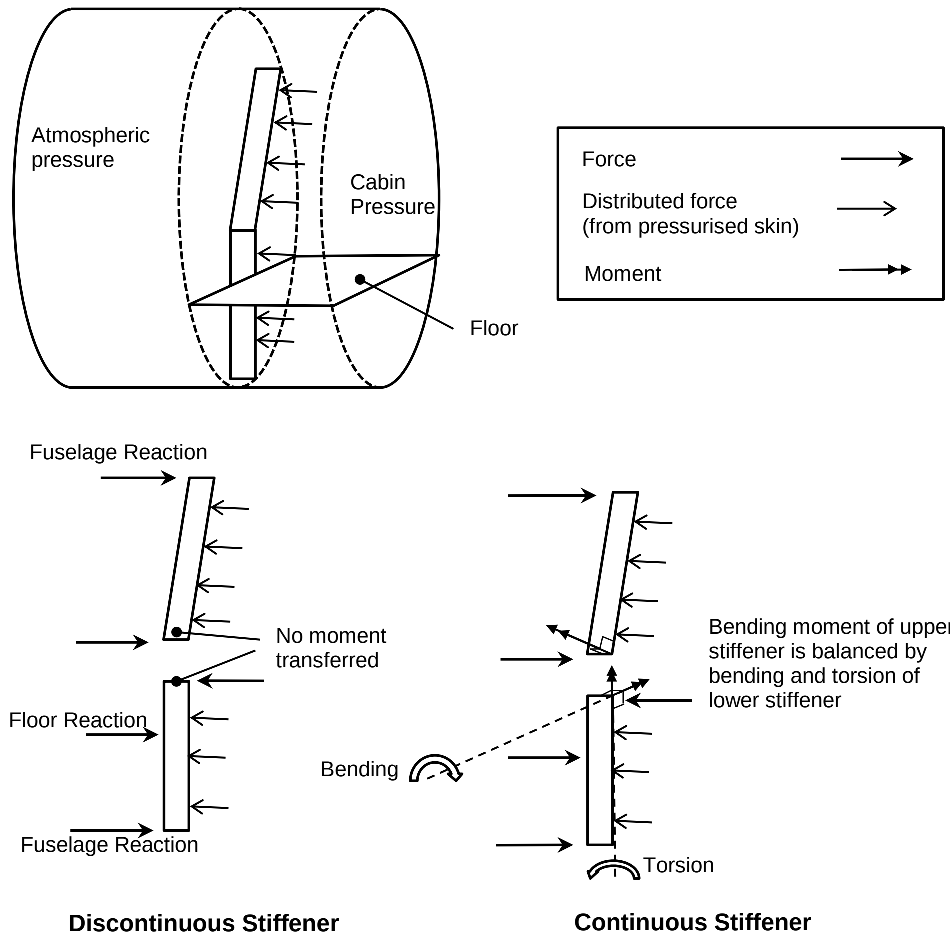


Figure 4.11 : Creation of torsion for curved continuous stiffeners

4.4.3 Exploration of topology with disconnected design space at floor

The effect of floor on discontinuity and orientation is due to the continuity of the design space on both side of the floor which creates a zone with no bending moment. In order to observe the behavior of a topology without this particularity, an optimization is performed where the design space above floor is disconnected from the design space below floor. Both design space are optimized to minimize compliance for a volume fraction of 20% each (Figure 4.12). This recalls that a return to the topology exploration phase can be necessary when new information is available. The new iteration is thus allowed and encouraged by the design process.

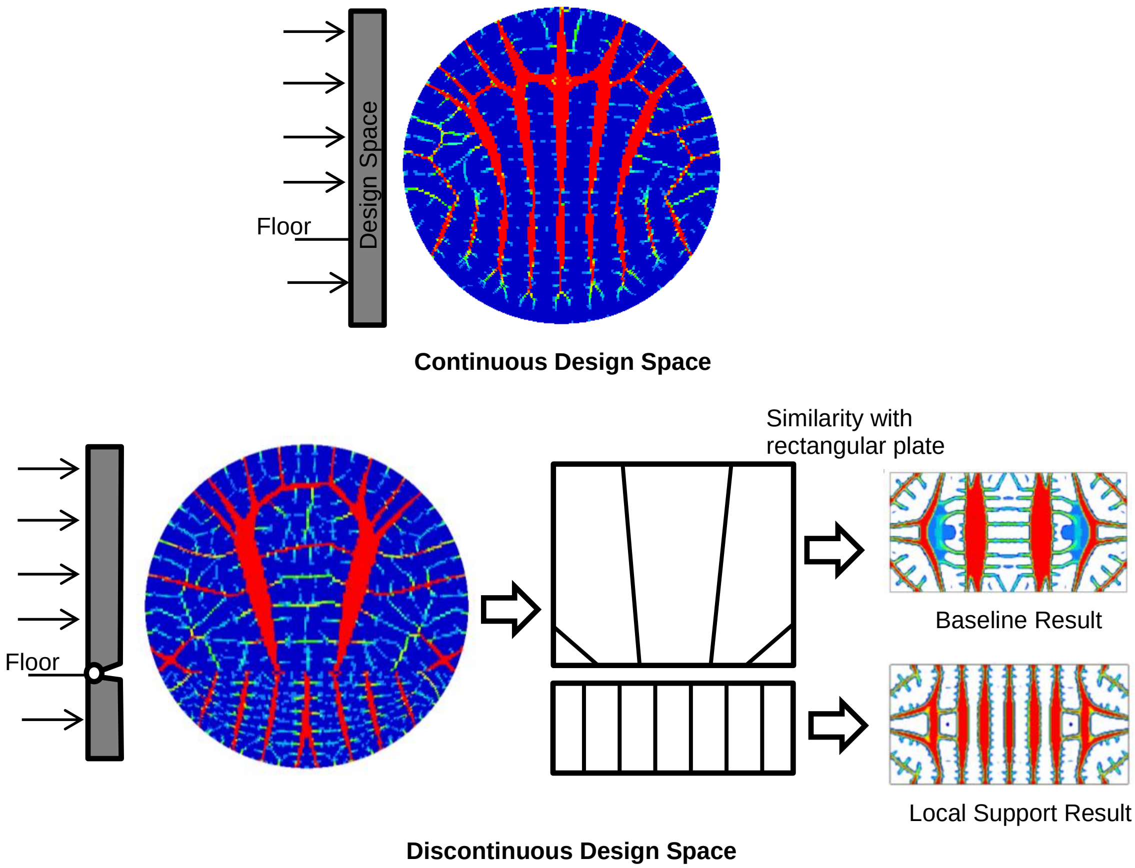


Figure 4.12 : Effect of disconnecting design space at floor

As expected, the discontinuities above floor disappear since the stiffeners above and below floor are independent. In fact, the design problem consists of the stiffening of two independent simply supported pressurized plates. The similarity of the stiffening layout with the rectangular pressurized plate presented in Chapter 2 is highlighted in the figure. One can note that the stiffening layout below floor recalls the regularly spaced design and the layout above floor reminds the design with two large stiffeners in the center portion. This highlights the importance of the relative stiffness of the boundary condition since the impact of floor is important on the lower portion but negligible on the upper. Finally, this modification of the design space allows once again a better understanding of the optimal stiffening.

4.4.4 Development of sub FRs

The detailed analysis of the topology result performed in this section allowed a better understanding of the functionality of the features observed. The stiffener discontinuity and orientation change are particular solution and no FRs can be directly associated to these features. However, the impact of floor on the layout is now well understood which allows defining the sub FRs inspired from the topology exploration as shown in Figure 4.13. These FRs are also the result of the "zag” from DP2 according to the axiomatic decomposition process described in section 3.1.3. Topology explorations highlighted that the stiffening need above (FR2.1) and below floor (FR2.2) are different which is the reason why different FRs are assigned to them. The addition of stiffeners also creates skin bays where local deformation has to be limited (FR2.3) which is a known FR for stiffened panels.

FR2	Sustain and carry load
FR2.1	Support deformation above floor
FR2.2	Support deformation below floor
FR2.3	Support local skin deformation

Figure 4.13 : Development of FR2.X of the bulkhead

Although these FRs might seem obvious, it is important to remind that they are the result of a systematic exploration of the design space. The functional interpretation step is just efficiently simplifying the complex feature observed into basic functionality.

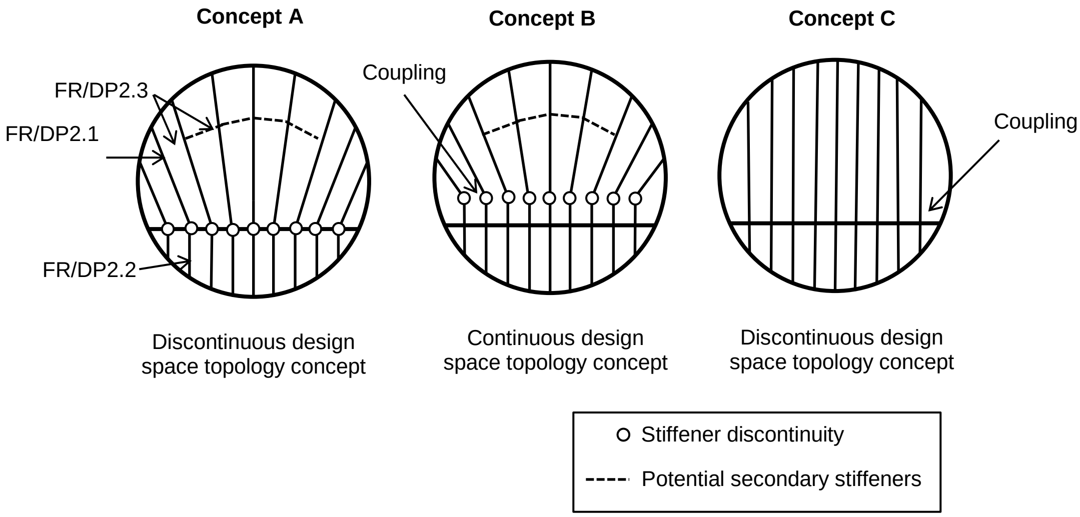
4.5 Physical interpretation

The knowledge acquired from the topology exploration and functional interpretation allows defining DPs associated to FRs 2.X. Three different concepts inspired are presented in Figure 4.14.

Concept A presents the interpretation of a design where stiffeners are disconnected at floor location. Concept B presents the interpretation of the topology intent when stiffeners are discontinuous above floor. Concept C presents an engineering solution fulfilling the FRs by using continuous and straight stiffeners. A detailed description of each design follows.

In all concepts, the support of the deformation below floor (FR2.2) is fulfilled by using vertical stiffeners placed at floor beam location (DP2.2). Vertical stiffeners are selected instead of allowing slight orientation change as suggested in the topology layout. This design decision is made in order to simplify the allocation of space of systems passing under the floor and between floor beams in order to respect CON2 (Allow system penetration). Note that a different solution could have been used to fulfill FR2.2 while respecting CON2. It is only important to remember that the new process will always be able to capture such constraints and consider it for the interpretation. Finally, the stiffeners are attached to the lower fuselage in order to adequately support skin bay (FR2.3) even is it not directly suggested in all topology layouts.

The support of the portion above floor (FR2.1) is fulfilled by different stiffener layout (DP2.1) for each concept. However, all layouts have regularly distributed stiffeners in order to fulfill the local skin support functionality (FR2.3). Concept A and B are similar since the stiffeners are discontinuous and have variable orientation as suggested by the topology. However, Concept A is completely decoupled since the lower and upper stiffeners fulfill their respective functionality independently. Concept B benefits from a reduction of upper stiffener length but introduces coupling. Concept C is inspired from typical designs where the upper portion of the stiffener benefits from the support (close to clamping) provided by its continuity. As discussed earlier, this continuity requires using straight beams to avoid problems related to torsion. This design is also introducing coupling but benefits from a regular skin bay division which makes the fulfillment of FR2.3 (Support local skin deformation) easier. The design matrix highlights the coupling between FR2.3 (Local skin support) and all DPs. This coupling is unavoidable since stiffener will always affect bay dimension. The matrix also highlights how concept B and C have coupled matrix because of the interaction between DP2.2 (Stiffeners below floor) and FR2.1 (Support above floor).



FR2	Sustain and carry load	DP2	Stiffener configuration
FR2.1	Support deformation above floor	DP2.1	Stiffeners above floor
FR2.2	Support global deformation below floor	DP2.2	Vertical Stiffeners below floor
FR2.3	Support local skin deformation	DP2.3	Bay dimension/Secondary stiffeners

	DP2.1	DP2.2	DP2.3
FR2.1	ABC	**BC**[8]	
FR2.2		ABC	
FR2.3	ABC	ABC	ABC

Figure 4.14: Physical interpretation and design concept of bulkhead stiffening

[8] Coupled design matrix for concept B and C

Table 4.1 illustrates a qualitative comparison of the design concepts presented. Concept A is used as the reference and different aspect of the design are compared. It is obvious that proper manufacturing and assembly of the beam discontinuity for concept A and B is more complicated than for concept C. The mass of the upper stiffener of layout B and C is lower than for layout A since they benefit from length reduction and clamping respectively. However, the coupling in these layouts will result in higher mass for lower stiffeners. Coupling is introducing complexity in the design and analysis which is seen as a negative aspect compared to concept A. Finally, the simple bay dimension control of concept C is advantageous compared the two other. This simple bay dimension control recalls the second axiom (minimisation of information and maximisation of the chances of success) as it can achieve the same bay support functionality (FR2.3) with less information. The table shows that Concept C has the best score for the aspect considered. It does not mean that it is the best design since a detailed sizing analysis would be required to assess performance. However, it highlights the conceptual advantages that concept C has over the others which can maximize its chances of success.

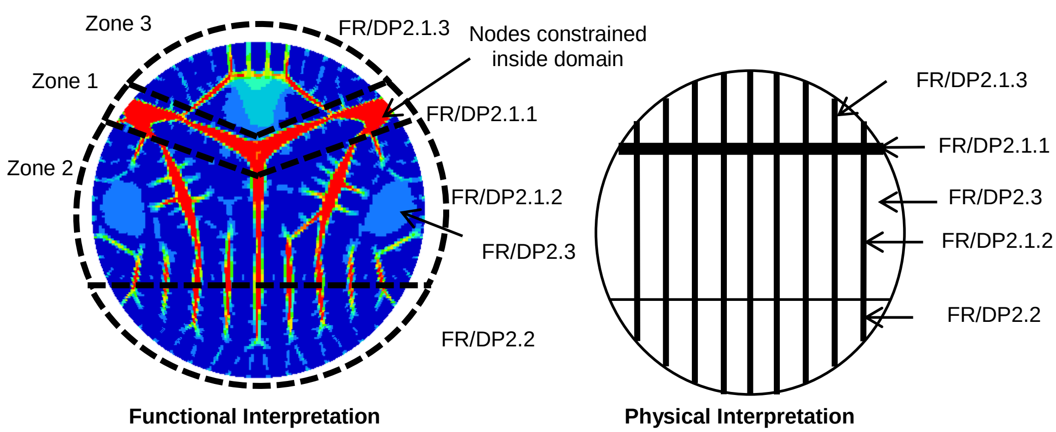
Table 4.1 : Qualitative comparison of concepts (Baseline: Concept A, +1:Better, -1: Worse)

	Concept B	Concept C
Manufacturing	0	+1
Bay dimension control	0	+1
Coupling	-1	-1
Upper stiffener mass	+1	+1
Lower stiffener mass	-1	-1
Total	**-1**	**+1**

4.6 On the other local boundary condition effect (Door Intercostal)

The process has been properly applied to the design case and three different concepts were presented. The following example aims at showing how the concept obtained can be significantly affected when considering the surrounding environment of the bulkhead. The last can highlight different boundary conditions which can have a major impact on the evolution of the topology and converge towards other local optimums.

The example is inspired from a real aft aircraft pressure bulkhead where local stiffness is introduced by the presence of a door intercostal. This intercostal reinforces the fuselage near door cut-outs and passes through the bulkhead skin due to its proximity with the door. It is modelled in the topology problem by constraining the out of plane translation of nodes inside the design domain. The constraints are applied on both sides of the fuselage in order to force a symmetrical design. Figure 4.15 shows the resulting topology along with its functional and physical interpretation. The topology iterations show that the horizontal stiffener is forming from the door intercostal location and therefore results in another local optimum. The functional interpretation of the layout is affected since the location of the intercostal plays a major role in the stiffening configuration. Therefore, the functions of the stiffeners above floor (DP2.1) are developed by considering different zones based on the location of the intercostal. A potential physical interpretation is also presented where the functional requirements are fulfilled by using simple straight beams as it was the case for concept C. The addition of a horizontal stiffener in zone 1 is the feature added in that case.



FR2	Sustain and carry load	DP2	Stiffener configuration
FR2.1	Support deformation above floor	DP2.1	Stiffeners above floor
FR2.1.1	Support deformation in zone 1 (Intercostal height position)	DP2.1.1	Horizontal stiffener in zone 1
FR2.1.2	Support deformation in zone 2 (Between floor and intercostal position)	DP2.1.2	Stiffeners in zone 2
FR2.1.3	Support deformation in zone 3 (Between top fuse and intercostal position)	DP2.1.2	Stiffeners in zone 3
FR2.2	Support deformation below floor	DP2.2	Vertical Stiffeners below floor
FR2.3	Support local skin deformation	DP2.3	Bay dimension/Secondary stiffeners

Figure 4.15 : Effect of modifying local boundary condition (FR/DP3) on design concept

This simple interpretation may seem far from the topology result but fulfills the same functionality as it also benefit from the local stiffness of the intercostal. Many other physical interpretations could be performed but it is not the objective of this example. The objective was to show how topology can be affected by local boundary condition and highlight unexpected load path which can result in different functional and physical interpretation.

Figure 4.16 illustrates an actual design of stiffener layout on a pressure bulkhead with similar boundary conditions. Notice that a large horizontal beam is placed at the intercostal location. In fact, this beam challenges CON1 (constraint on allowable design space for bulkhead depth) since space for systems was not required at this height behind the bulkhead. This large beam actually provides a support to the vertical beams and its functionality is therefore coupled. This design solution could never be obtained by the topology optimization as it is converging to different local optimums and the design space does not allow such local violation of CON 1. However, topology proved to be efficient at highlighting stiff supports and potential load path which could lead to such design if functionality is well interpreted and if engineering knowledge is used to perform the physical interpretation.

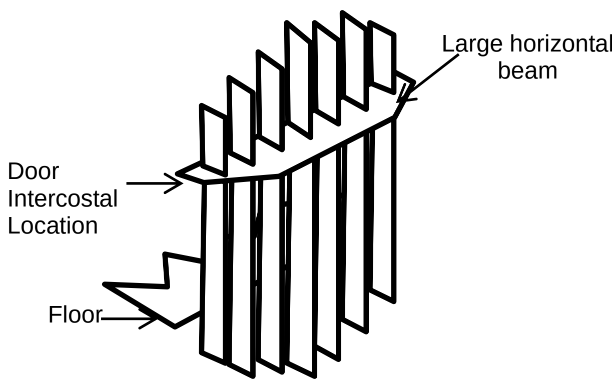


Figure 4.16 : Existing design with similar boundary conditions

4.7 Synthesis and discussion

The former chapter showed how the process developed is applied to the aircraft pressure bulkhead. Figure 4.17 summarizes each step of the process performed in this chapter. The definition of the **customer needs** and its interpretation into **first level FRs, DPs** and constraints forces the designer to understand the design problem and supports the generation of a topology optimization model. The topology **exploration** phase highlights potential load path and reduce risk associated to local optimums since it includes an evaluation of layout sensitivity. The **functional interpretation** investigates the origin of redundant features in order to understand their functionality and define sub level FRs. In that design case, the effect of floor on the layout was major and a feedback loop toward the topology exploration phase was used to better understand the behavior observed. Finally, the **physical interpretation** facilitates the interpretation of a topology layout while considering design constraints and avoiding coupling. In this case, three different solutions fulfilling the defined FRs were presented. Many other solutions could have been proposed but they would all have aimed at fulfilling the functionality defined after exploring the design space. The respect of constraints and coupling will affect the selection of a solution over another.

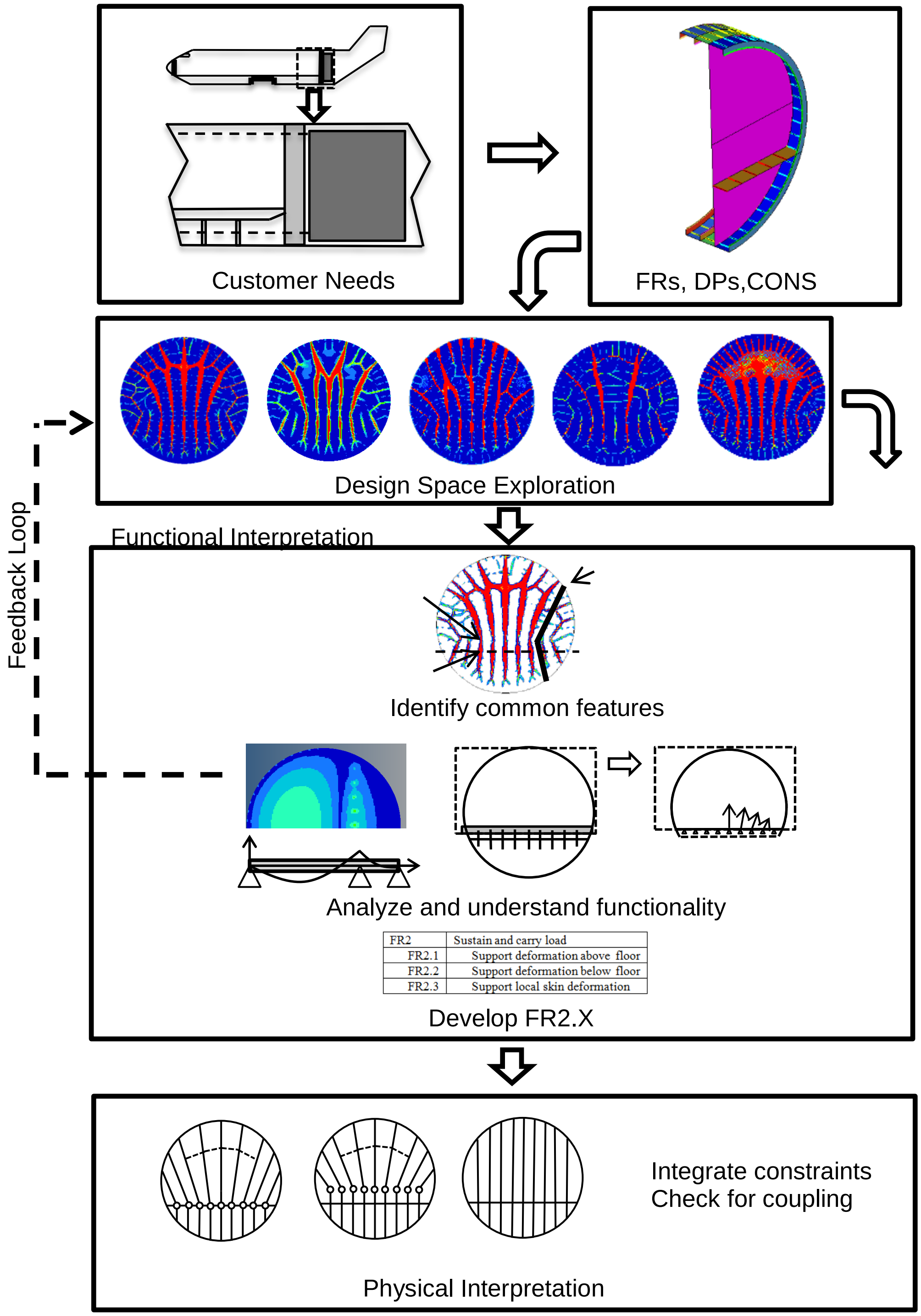


Figure 4.17 : Synthesis of the applied design process

The process can be generalized because it is applicable to any structural design case. The main steps do not change and the feedback loops can account for new information appearing during the development of a product. It can be efficiently used to reduce the large initial design space while exploring it in an innovative way. It also supports the topology optimization tool which cannot handle the whole concept generation phase by itself. Following the new process will always lead to feasible design concepts inspired from topology optimization that respects constraints and fulfills the required functionality while reducing risk associated to local optimality. The second research hypothesis is therefore confirmed since combining topology optimization to axiomatic design principles resulted in a design process that addressed and overcame the main identified challenges.

Finally, the objective of this application of the design process is partially achieved since a final design was not fully demonstrated. However, the most challenging and innovative aspect that consists of generating design concept was addressed. The detailed design and analysis of the design concept can be achieved by using standard and well established aerospace structural analysis methodology along with size and shape optimization technology as discussed in section presented in section 3.2.

CHAPTER 5 GENERAL DISCUSSION

The objective of this thesis was to explore the application of topology optimization for the design of an aircraft's pressure bulkhead and develop a design process based on the acquired knowledge.

According to the literature reviewed, the application of topology optimization to determine the optimal stiffener layout on a pressurized plate on a complete case study (from concept to sizing) was not explored. It was therefore important for this thesis to investigate the application of topology optimization as it is the primary load case on a pressure bulkhead. This study allowed to better understand the topology optimization design process and its associated challenges for this type of load. The acquired knowledge can then be used to develop the new design process.

A simple design case inspired from the pressure bulkhead was first defined with a realistic design space and engineering constraints such as maximum stress and displacement. In order to obtain a fair comparison basis, a typical and intuitive design was also defined. The design space was then explored using topology optimization to generate new design concepts. The performance of the concepts obtained with topology optimization was finally compared with the typical design.

This study allowed identifying several challenges associated to the pressurized plate case. The non-linearity of the deformation of the thin skin between stiffeners due to the membrane stiffening effect cannot be captured by the SIMP method. Moreover, the method uses a gradient optimizer that cannot explore the whole design space as it converges towards the first local optimum. This investigation also allowed identifying challenges associated to the generation and interpretation of the topology. The topology result proved to be very sensitive to the different optimization parameters. In other words, the topology was sometimes giving completely different answer to a very similar problem. Also, the topology result is not directly interpretable into a feasible design. The formation of many stiffeners and the connectivity between them makes the understanding of their individual functionality in the complete layout difficult. Finally, the performance comparison showed that the topology design has at most a mass that is similar to the typical design. It raises a flag concerning the efficiency of topology optimization to generate optimal stiffener layout for pressurized plates. It also highlighted the importance of having a more global understanding of the design problem when selecting and interpreting topology optimizations. The understanding of the functionality of the redundant features generated proved to be essential in order to perform a good interpretation and reach good performance.

As mentioned earlier, the knowledge acquired concerning the challenges and limitations of topology optimization for the design of stiffened pressurized plates has been used to develop the new design process. The need for a better understanding of functionality encouraged the use of another design approach to support the topology optimization design process: Axiomatic Design. This methodology focusing on product functionality was well-suited to address the main challenge identified. The design process was then defined with the idea that topology optimization would only be used as a tool to explore the design space in the axiomatic design framework. This allowed introducing a design space exploration phase aiming at overcoming the local optimality of the topology result by forcing the designer to perform several different optimizations. In order to support the interpretation challenges, the functional interpretation phase was defined. This phase requires the designer to identify common feature and understand their main functionality. This allows stepping back from the topology results and avoids a direct interpretation of a local optimum. Once the functionality of the features are defined, the physical interpretation naturally result in a design concept that is feasible and that respects design constraints and axiomatic design principles.

In summary, the paper presented has a major importance in this thesis as it allowed understanding the application of the topology design process and its limitation for the stiffening of pressurized plates. This exploration was necessary as the literature reviewed did not offer enough information concerning the challenges and the performance of topology optimization for the type of structures studied. It allowed identifying several difficulties which were finally used to develop and innovative design process. The design process addresses the challenges and suggests a new systematic approach or the design with topology optimization based on axiomatic design principles.

CONCLUSION

The objective of the thesis was to investigate the application of topology optimization for the design of a rear pressure bulkhead and develop a new design process based on the knowledge acquired.

The literature review highlighted the knowledge gap concerning the use of topology optimization for the design of flat pressurized stiffened plates which led to the first research question: how does the topology optimization design process performs compared to a typical design for flat pressurized stiffened plates? This question was addressed by simplifying the bulkhead into a rectangular pressurized plate. The difficulties of generating and interpreting a topology layout were presented. Moreover, the topology design did not result in significant weight reduction compared to a typical design. The study also highlighted the necessity of considering several topologies to account for local optimality. It showed the importance of understanding the functionality of features observed when interpreting the topology result into a design concept. The research hypothesis is infirmed since topology did not improve performance compared to a typical design. Finally, the findings of this study were shared with the scientific community through a submitted journal paper.

The knowledge acquired on the simplified plate example was used for the second research question: how to address the challenges of the actual topology optimization design process? A new design process was developed where topology optimization is used as a tool within the axiomatic design framework to identify potential design solutions and develop the functional requirements of the structure. This functional interpretation forces the designer to understand the origin of the features observed and avoids a direct interpretation of the topology. The physical interpretation then comes naturally while integrating design constraints, limiting coupling and maximising the chances of success. The process was successfully applied to generate design concepts for the pressure bulkhead and proved to support and add value to the topology optimization tool. This application confirms the research hypothesis stating the combining topology optimization to axiomatic design can be successful to overcome the challenges of the topology design process. This work contributes to the improvement of topology optimization based design as it provides a new and systematic methodology to generate design concepts. It is also the first proposal of combining axiomatic design and topology optimization which are two powerful conceptual design approaches. The process can be generalized to any structure and has therefore a large application potential.

Future work

The application of topology optimization for the design of flat pressurized plate allowed the identification of several areas for future work. Density topology optimization could be used with a non-linear analysis and an evolutionary optimization solver in order to capture the non-linearity of the pressurized plate problem and explore other local optimums more efficiently. On the other hand, other optimization method could be suggested to explore the design space such as sizing optimization of a predetermined iso-grid pattern. The effect of combining in-plane loading to the pressure load could also be explored in further studies where more complex loading and design spaces are defined.

The new design process proved to be efficient to generate design concepts but its support of the detailed design phase was not shown. For now, the process suggests using typical size and shape optimization along with detailed analysis to bring design concepts towards final designs. However, the axiomatic design principles could also be used to develop the functional decomposition and support the detailed design phase. It would be interesting to explore this avenue in future work on the design process. Finally, the proposed process was not applied to a large number of design cases and its use on other type of structures would be required to reach maturity.

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APPENDIX A – Simplified pressure bulkhead model

Model Description

The model represents a simplified business aircraft rear pressure bulkhead. A section of the fuselage surrounding the design space is modeled in order to obtain representative boundary condition for the topology design space. The pressure is applied to the bulkhead skin and forward fuselage. Local structure such as fuselage frame flange and floor beams are modeled with CROD element allowing only tension and compression stiffness. Fuselage stringers are modelled by CBEAM element with circular cross section to ensure bending stiffness under pressure load. All shell elements have a thickness of 2mm. All dimensions and properties are showed in Figure A.1 and are inspired from the real pressure bulkhead presented later in this chapter. The absolute value of these properties is not important but the relative stiffness between them is. For example, the floor beam rods are stiffer than the floor skin and this can favor this load path for the support of stiffeners.

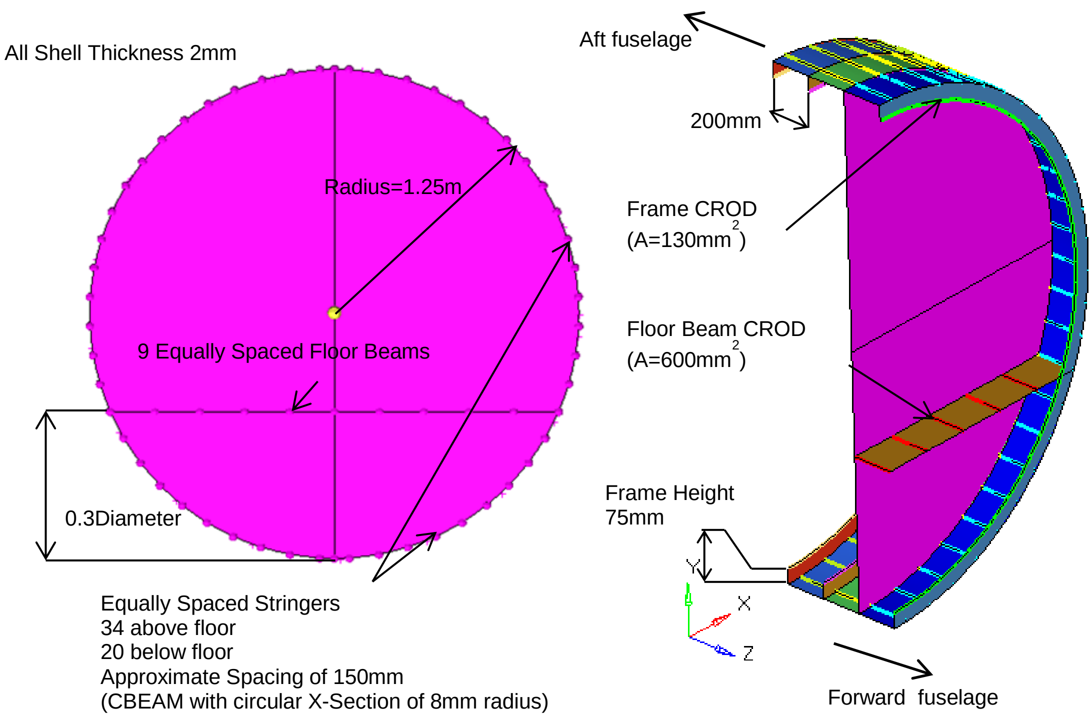

Figure A.1 : Simplified bulkhead model dimensions

Boundary conditions

Particular finite element practices are used to represent the expansion of the section of the fuselage. Figure A.2 describes the modeling technique used to represent load and boundary conditions. The forward fuselage edge nodes are constrained to simulate symmetry in the XY plane (Single-Point Constraint (SPC) 345). The aft edge nodes are constrained for symmetry in the XY plane but allow free Z translation to avoid introducing compression in fuselage skin (SPC 45). These two symmetries are not constraining the model for XY plane translation and Z axis rotation. In order to do so without constraining the expansion of fuselage under pressure, the stringer nodes at forward fuselage section cut are linked together with an interpolation element (RBE3). This is a common modeling approach to link nodes together without bringing additional stiffness to the model. The displacement of the central node (dependent) becomes function of the displacement of all stringer nodes (independent). The dependent node is attached in space with a high stiffness spring element (CBUSH). The use of spring element with high stiffness is required because a dependent DOF cannot be dependent of another rigid element. The free node of this spring element is constrained with the missing DOF. This set of elements and constraints allows fuselage expansion under pressure and avoid rigid body motion of the model in space. This can therefore provide realistic boundary conditions to the topology design space with a simplified model.

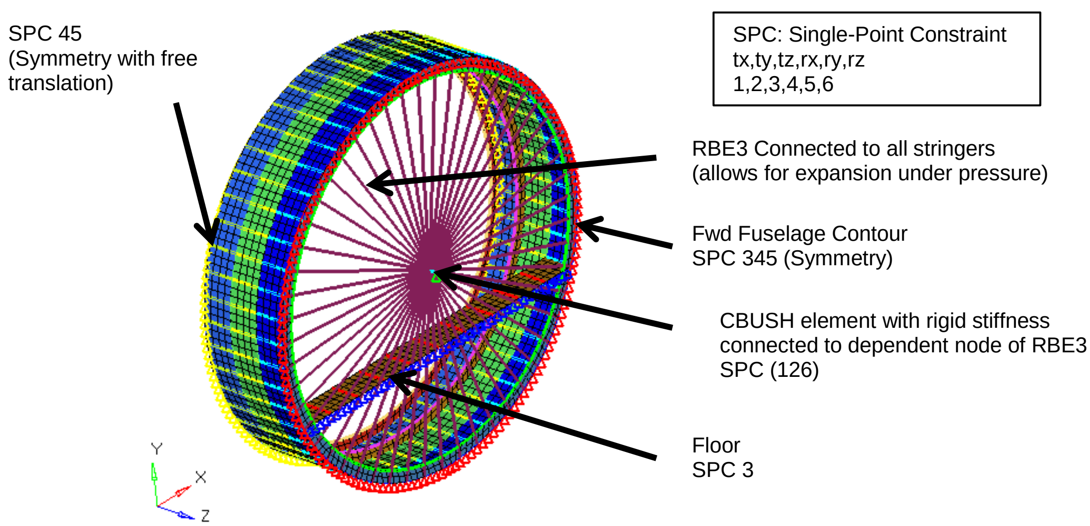

Figure A.2 : Simplified bulkhead finite element attachment in space